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Determination of relationship between basement faults and alteration zones in Bafq-Esfordi region, central Iran

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The remote sensing was utilized for mineral exploration specifically to look for the presence of altered minerals. In addition, airborne magnetic data have been used for modelling of basement faults/structures. Furthermore, these data provide a synoptic view, which is helpful in the identification and delineation of various land forms, linear features and structural elements. Moreover, mapping geological lineaments is essential for regional exploration of hydrothermal deposits. The aim of this study is the determination of relationship between faults/structures and hydrothermal alteration zones based on geophysical and remote sensing data in the Esfordi area, central Iran. Basement faults were extracted by magnetic airborne data and alteration zones were detected using remote sensing data. Statistical and geostatistical parameters were determined in this area including correlation between areas of alteration zones and distances to faults, variograms and anisotropic ellipsoid. These reveal that there is a direct correlation between alteration zones and basement faults in the study area.

Introduction

The multi spectral image is widely used for mineral exploration, specifically to individuate the presence of altered minerals such as alunite, pyrophyllite, kaolinite, sericite, illite and muscovite (Salem et al., 2013). We used it in combination with airborne magnetic data for the determination of basement rocks and faults/structures deeper than 1 km. The airborne geophysical data play a basic role in fault/structural modelling in depth, estimating basement's depth, lithological boundaries, delineation of the deep ore bodies, and modelling of buried fault. In addition, this data provides a synoptic view, which is helpful in identification and delineation of various land forms, linear features and structural elements (Javed and Wani, 2009; Adham et al., 2010). Hence, mapping geologic lineaments is important for identification of alterations (Green et al., 1988; Kujjo, 2010).

Iran is located in the Alpine-Himalayan orogenic and metallogenic belt and hosts base and rare metals deposits. Multi spectral images have been used by researchers for interpretation of the structural features and exploration purposes (Abrams, 2000; Asadi et al., 2007; Azizi et al., 2010; Rajendran et al., 2012). The main aim of this study is the determination of relationship between faults/structures and hydrothermal alteration zones in Esfordi 1:100,000 sheet, central Iran, based on geophysical and remote sensing data.

Geological Setting

The Esfordi region (Figs. 1 and 2) is located 30 Km east of the city of Bafq, Central Iran. The structural domains occurring in this area include the Anarak-Bafq-Kerman metallogenic belt (Berberian, 1981). The crustal domain referred to as the Central Iranian microcontinent is a composite of three major structural zones, from E to W (Alavi, 1991) including Lut, Tabas, and Yazd blocks (Fig. 1b). In addition, there is Posht-e-Badam Block (Alavi, 1991), as a fault-bound, variably deformed and metamorphosed complex of supracrustal rocks that separates the Tabas and Yazd blocks. Alternatively, (Ramezani and Tucker, 2003) defined the Kashmar-Kerman structural zone between the Yazd and Tabas blocks, coinciding with the eastern portion of the Posht-e-Badam Block of (Alavi, 1991) but with slightly different boundaries: the Kuhbanan-Kalmard Fault to the E and the Posht-e-Badam Fault to the W (Fig. 1b). The Posht-e-Badam Block is located within an area defined between three major fault systems (Alavi, 1991): Chapedony, Kalmard and Kuhbanan faults (Fig. 1b). A Precambrian crystalline basement and Early Cambrian to Tertiary sedimentary cover are exposed in this block (Forster and Jafarzadeh, 1994). The Precambrian basement consists of medium to high-grade metamorphic rocks, Late Neoproterozoic in age, grouped in the Boneh-Shurow and Posht-e-Badam complexes (Ramezani and Tucker, 2003; Verdel et al., 2007). The Posht-e-Badam complex consists of an association of green rocks (e.g., amphibolite, pyroxenite), schists, meta-greywackes, marbles, gneisses, amphibolites, pyroxenites, serpentinites, meta-basalts, and conglomerates (Haghipour and Pelissier, 1977). This complex is exposed in the

Figure 1. (a) Tectonic scheme of Iran's sedimentary basins (modified from Arian, 2013). (b) Geological map of Posht-e-Badam block, part of Yazd and Tabas blocks with the major faults (Rajabi et al., 2012a), including the Behabad, Kuhbanan, Kalmard, Posht-e-Badam Faults. Main ore deposits are highlighted in the map. The red dashed line rectangle is the extent of the study area.

west of the Posht-e-Badam fault and is intruded by Triassic granitic plutons (Ramezani and Tucker, 2003). The Boneh-Shurow complex, which is the most widely exposed metamorphic unit, crops out in the east of the Posht-e-Badam Fault (Fig. 1b; Haghipour and Pelissier, 1977). This complex is approximately 2000 m thick and exhibits a variety of metamorphic rocks, including quartz-feldspathic gneisses, green micaschists and amphibolites (Aghanabati, 2008). The U/Pb dating of this complex indicates a metamorphic age of 602–617 Ma (Ramezani and Tucker, 2003). The Boneh-Shurow complex is covered by a 2000-m thick sequence of greywackes, quartzites and quartzitic schists, marbles, amphibolites, gneiss, slaty-shales, basaltic lavas, sandstones and arkosic arenites, argillites, tuffaceous rocks, as well as limestones of Late Neoproterozoic to Early Cambrian age (Ramezani and Tucker, 2003) that is partly metamorphosed to the greenschist facies. During the Early Cambrian, granitic plutons intruded into the Precambrian sequence of the Tashk formation, and felsic to intermediate volcanic and volcano-sedimentary rocks of the Early Cambrian Volcano-Sedimentary Sequence (ECVSS) were deposited (Daliran et al., 2009). This contact is well exposed in the W and SW of the Narigan area. The ECVSS has also been termed the Cambrian Volcano-Sedimentary Unit (CVSU), Rizu-Desu series and Esfordi Formation, in different parts of the area between the Posht-e-Badam and Kerman areas (Huckriede et al., 1962; Haghipour, 1977; Samani, 1993; Ramezani and Tucker, 2003). The ECVSS consists of an unmetamorphosed sequence of interlayered micro-conglomerates, sandstones, mafic to felsic volcanic rocks, pyritic black siltstones and shales, volcanoclastic beds and tuffaceous shales, dolomites and dolomitic limestones (Haghipour, 1974; Ramezani

and Tucker, 2003; Rajabi, 2012). This sequence is host to the most important IOA (Iron Oxide Apatite; Daliran et al., 2009), Fe-Mn and SEDEX Zn-Pb deposits of Iran (Fig. 1b; Rajabi et al., 2012a; Rajabi, 2012; Adib et al., 2017). The upper carbonates of the ECVSS are uncomfortably overlain, in the Zarigan and Chahmir areas, by red conglomerates, sandstones and shales of the Early Cambrian Dahu also called as the Lalun Formation, and by the Middle Cambrian trilobite-bearing Mila Formation (Forster and Jafarzadeh, 1994; Rajabi, 2012). Late Cambrian, Silurian–Permian and Triassic rocks are identified in the region. Rocks of the Jurassic Shemshak formation are exposed in the Chahmir and Koushk areas (Rajabi, 2015); in this place, these rocks are folded and overthrust by materials of the ECVSS (Rajabi, 2008; Rajabi et al., 2012a), indicating a main post-Cimmerian orogenic event (Aghanabati, 2004). Cretaceous carbonate rocks overlie western parts of the region forming prominent cliffs east and northeast of Bafq. There are mineralizations of different types of iron ores (> 2 Gt) which are located in the Bafq district. The largest reserve of iron ore in Bafq region is Chadormalu mine which contains 400 Mt of iron ore (Haghipour, 1977; Samani, 1993; Forster and Jafarzadeh, 1994).

The Bafq region is one of the most important metallogenic zones of Iran which includes the upper Precambrian metamorphic sedimentary rocks and Rift series of Precambrian–Paleozoic (Haghipour, 1977). Central Iran structural zone is a portion of Gondwana land with a Precambrian basement consisting of ignimbrites, ring fracture intrusions, and granites (Fig. 2; Forster and Jafarzadeh, 1994; Daliran et al., 2010). Intrusive rocks host magnetite, apatite-magnetite and Rare Earth Elements (REEs) mineralizations. These mineralized zones are commonly

Figure 2. Geological map of study area based on 1:100,000 geological map of Esfordi. This area has shown in Figure 1b by a red dashed rectangle.

associated with calc-alkaline volcanic rocks and metasomatic alteration of the host rocks. Iron oxide-apatite deposits occur within felsic volcanic tuffs and volcano-sedimentary sequences of the Early Cambrian age (Stosch et al., 2011; Sadeghi et al., 2013). The magnetite-apatite deposits occur in form of several orebodies with large scale replacement and brecciation textures, and a sodic-calcic alteration envelope (Stosch et al., 2011). Previous studies show that the genesis of the iron ores is similar to Kiruna-type deposit (Forster and Jafarzadeh, 1994; Daliran et al., 2010). There are several large and rich iron and iron-apatite deposits and occurrences around the Bafq region, e.g., Chadormalu, Choghart, Seh-Chahoon and Chah-Gaz iron ores and the Esfordi iron-apatite ore deposits (Fig. 1).

The study area occurs in the Bafq mining district, which is part of the narrow N-S trending Pan-African rift zone. Berberian and King (1981) suggested that the development of this rift zone was the result of stretching of the Arabian-Iranian continental crust during an Infra-Cambrian extensional phase. Forster and Jafarzadeh (1994) suggested that the centers of magmatic activity and maximum crustal thinning coincided with the axis of this assumed rift (Moore and Modabberi,

2003). There are no continuous sedimentary covers because the compressional phases (Cimmerian and later Alpine orogenies) occurred after continental rifting during late Pre-Cambrian to Paleozoic and caused severe erosion.

Also, the related rock units have been widely eroded by later compressional stages in Mesozoic and Cenozoic times, related to the formation of the Yazd-Khour Piggy back basin (Arian, 2013). The dominant trend of faults in this zone is nearly NW-SE and it has been affected by convergent processes during the collision of Cimmerian block with Eurasia since late Triassic from its north margin and the Arabian-Cimmerian collision since late Cretaceous from its south margin.

Therefore, despite that, from Pre-Cambrian up to present, there were several episodes of magmatism and mineralization, the orebodies and hosted rocks (Infra-Cambrian) have been preserved as the main exposed rocks in the study area. Local faults that crosscut the ore bodies have been already partially investigated at the mine scale by some researchers e.g., Daliran et al. (2009, 2010) Moore and Modabberi (2003) and Forster and Jafarzadeh (1994). With this work we add several information by large scale remote sensing investigation of lineaments and faults.

Figure 3. Spectral library plots from USGS library.

Datasets and Methodology

The ASTER is an advanced remote sensing sensor which consists of 14 spectral channels varying from the visible to thermal infrared (Watanab and Matsuo, 2011). Different factors are affect signal processing at the sensor such as radiometric calibration, atmospheric and topographical effects. At last, a data set including AST_LIT_00306102002070344_20150422202108_63722 in hierarchical data format (HDF) was utilized for this study and radiance correlation consisting of wavelength, dark subtract and log residual was carried out, which is important for multispectral images, and was implemented in this research by ENVI4.8 software.

The magnetometric data with a flight height of 120 m and a nominal flight line spacing of 500 m in N45, is provided by Atomic Energy organization. Magnetic data have been prepared after correction of the mea-

surements for the daily correction, elimination of the 1975 model of the IGRF (International Geomagnetic Reference Field), and alignment of the magnetic field (Fig. 5).

The Spectral Angle Mapper (SAM) method is a classification technique that allows rapid mapping by calculating the spectral similarity between the image spectrums and to reference reflectance spectra. The SAM measures the spectral similarity by calculating the angle between the two spectra, treating them as vectors in n-dimensional space (Kruse et al., 1993; Pour and Hashim, 2012). The image spectra were compared with USGS Digital Spectral Library (Minerals) (Malekzadeh et al., 2009). Figure 3 shows selected minerals spectral library plots related to iron oxide, argillic, phyllic and propylitic alterations.

The mineral spectral representatives of iron oxide include jarosite, limonite, hematite and goethite; argillic zone include kaolinite, dickite and halloysite; phyllic alteration namely illite and muscovite and also propylitic zone include epidote and chlorite were selected (Fig. 4).

Figure 4. The iron oxide, argillic, phyllic and propylitic alteration zones imaged by SAM method.

Results

The First Vertical Derivative (FVD)

The range of the magnetic field intensity gradient in different directions tends to sharpen the edges of anomalies and enhance shallow for the purpose of enhancing the surface anomaly toward shallow anomaly derivatives (Feumoe et al., 2012). The vertical derivative map is much more responsive to local influences than to broad or regional effects and therefore tends to offer a sharper picture compared to the map of the total field intensity. Thus, the smaller anomalies are more readily apparent in area of strong regional disturbances. The FVD is used to delineate high frequency features more clearly where they are shadowed by large amplitude, low frequency anomalies. The enhancement of magnetic anomalies associated with faults and other structural discontinuities were outlined by the application of the FVD to the residual map in Figure 5 (Dobrin and Savit, 1988). The reprocessed magnetic data set is significantly enhanced in high frequencies and is much better suited to detailed regional shallow mapping and analysis of basement magnetic boundaries.

Lineament Extraction

To delineate the subsurface structures of the Esfordi region, the air-

borne magnetometric data were used and interpreted. This geophysical approach is the FVD method to delineate linear structures. Then, it is incorporated with the shaded relief map model. The Results of this method are used to build a structural model to help in understanding the subsurface structure of the study area. So, the structure of basement faults, many of which being syn-tectonic, (Nabilou et al., 2018) is extracted (Fig. 5a) with the Oasis Montaj software. In Figure 5a, the trend of fault structures is NW-SE and the flower structures diagram (Fig. 5b), shows NW-SE direction. Integration of alteration and lineament (basement magnetic fault) with accordance to geology map of study area is shown in Figure 6. It appears that the direction of mineralized bodies and correlated alteration zones follows the same NW-SE trend of faults.

After extracting the iron oxide, argillic, phyllic and propylitic alterations as well as delineating the magnetic map lineament, all of these data have been merged (Fig. 6) in order to understand the structural relationships existing among them.

Spatial Data Analysis

As a general rule, mineral resource simulation requires suitable statistical tools for better investigation of spatial distribution. Some geostatistical methods are sensitive to the presence of trends in the variability of ore grades (Rossi and Deutsch, 2014). Variogram modelling and estimation is extremely important in structural analysis and spatial

Figure 5. Structural interpretation of magnetic data. (a) Extracted Magnetic basement fault on the magnetic using FVD method. The trend of basement fault is NW-SE. (b) Basement fault Rose diagram that shows direction of fault trend (NW).

Figure 6. Integration of alteration and magnetic map lineament (basement faults).

interpolation (Burrough and McDonnell, 1998). They are widely used tools for spatial interpolation, which in turn provide the fundamental parameters for geostatistical modelling (VerHoef and Cressie, 1993; Calder and Cressie, 2009; Shahbeik et al., 2014). A variogram map (Deutsch and Journel, 1998), which is a 2-D plot of the sample variogram for all experimentally variable separation vectors, was generated to understand the anisotropy of primary and secondary alterations in the region (Fig. 8). The experimental variogram displays several important features (Webster and Oliver, 2001). The variogram models may consist of simple models, including: Nugget, Exponential, Spherical, Gaussian, Linear, and Power model or the nested sum of one or more simple models (Burrough and McDonnell, 1998; Webster and Oliver, 2001; Pebesma, 2004). For understanding the alteration ellipsoidal anisotropy and its 2D semi-variogram plot, it is necessary to separate

all the population distributions of the alterations from each other with drawing separate polygons (Fig. 7). After that, all the alteration areas and the distance from their centers to the basement faults can be measured (Table 2).

In the current study the linear and exponential models were used. Continuity is a measure of geological properties against distance, which can be sensitive to the different directions as in alteration systems. The form of spatial variability in mineralization or alteration systems is called anisotropic behaviour because there is more continuity in one direction than in others. In numerous cases that alteration or mineralization forms to the faults and fractures, the variograms are directional and the deposit is anisotropic, in spatial directions and followed by the primary (Iron oxide) and secondary (Argillic and propylitic) alteration forms. In anisotropic deposits, the impact Domain (γ) is

Figure 7. Basement fault have extracted from Magnetic map with the alteration areas consisting of (a) iron oxide (b) argillic and propylitic for determination of the Ellipsoid anisotropy.

Figure 8. Anisotropic direction for alteration areas based on Ellipsoid Anisotropy and related semi-variogram (major and minor axis). (a) Iron oxide alteration anisotropy. The variogram is without nugget and the direction of the major axis of Ellipsoid anisotropy is NW-SE. (b) Argillic alteration anisotropy. The variogram is without nugget and the direction of the major axis of Ellipsoid anisotropy is NW-SE to N-S. (c) Propylitic alteration anisotropy. The variogram is without nugget and the direction of the major axis of Ellipsoid anisotropy is N-S.

in various directions. The variograms have different ranges which show anisotropy in this region and main observations are listed below:

- The iron oxide is anisotropic in the plane that the direction of the major axis is roughly 0° to North West and shows an isotropy in the orthogonal direction to this plane. The rose diagram trend of fault trend (Figs. 5a and b) and the direction of the major axis in ellipsoid anisotropy (Fig. 8a) is correlated with the basement main fault direction.
- The argillic alteration is nearly anisotropic in plan that the direction of the major axis is roughly 0° to North West near to north and shows an approximate isotropy in the orthogonal direction to this plane. The direction of the major axis in Ellipsoid anisotropy is close to the main fault trend in the basement.
- The propylitic alteration is isotropic in plan that shows anisotropy in the orthogonal direction to this plane. The direction of the major axis in ellipsoid anisotropy is Non-line of the direction of basement main fault (Fig. 8).

In this study, the most important alteration is Iron oxide alteration (Nabilou, 2017) because it is the primary alteration after Fe mineralization. Geostatistical parameters obtained for the Iron oxide alteration are thus discussed here in detail whereas data from the other alterations are reported only in Table 1. Iron oxide model consists of a 0 nugget effect, sill 23.5 and Major Axis Range 13212 m and minor axis Range 9715m. The variogram 0° to the first two directions is shown in Figure 8. It is observed to have a much shorter range of about 2700m. The ratio of the range of the major axis (Fig. 8a) to the minor axis (Fig. 6a and Table 1) is 1.36. Therefore, in the second stage, it

is crucial to detect possible trends of expanse of alteration areas that are determined with drawing polygons (Figs. 7a and b) after the determination of the alterations using the same method. However, the geo-statistical results about the iron oxide and argillic alteration indicate that they are anisotropic and with the same expanse to NW-SE direction in Ellipsoid anisotropy. On the contrary, the propylitic alteration shows its expanse in the N-S direction, which does not coincide with the trend of basement faults.

The correlation diagram is commonly used with forecasting purposes in mineral resources exploration and extraction. The spatial arrangement of alteration areas (iron oxide, Argillic and propylitic in Fig. 9) with respect to basement faults can be used to forecast the occurrence of ore bodies by using the correlation diagram and the associated linear equations. The linear regression is a kind of regression that is used in this study. Based on the correlation diagrams, the iron oxide and propylitic alterations' alteration areas increased with respect to decrease in the distances to the nearest basement fault (Figs. 9a and c). The argillic areas decreased when the distances to the nearest basement fault increased (Fig. 9b).

Discussion

To evaluate the ASTER satellite data, specific alteration zones and lineaments, field-checks have been performed. In almost all cases, our fieldwork indicated the real alteration and detected of area of linea-

Table 1. The table shows the measurement results of the alteration area and the distance of the center of the alteration area to the nearest basement fault

Iron Oxide										Argillic				
No.	X	Y	Distance (Km)	Area (km ²)	No.	X	Y	Distance (Km)	Area (km ²)	No.	X	Y	Distance (Km)	Area (km ²)
1I.OX.	365221	3535799	0.36	29.13	38I.OX.	363950	3524518	0.212	0.13	1A.	364053	3536058	0.156	5
2I.OX.	386941	3535504	3.957	0.02	39I.OX.	360349	3524512	0.494	0.44	2A.	367689	3531337	0.191	2.5
3 I.OX.	368047	3530462	0.216	3	40I.OX.	367777	3526504	0.052	3.75	3A.	366080	3522650	0.099	5.44
4I.OX.	370626	3530393	1.555	6.5	41I.OX.	366880	3522271	0.122	2.2	4A.	367925	3523670	0.065	0.54
5I.OX.	377064	3533048	0.2	19.24	42I.OX.	364388	3520569	1.31	4.15	5A.	370972	3523938	0.023	10
6I.OX.	378780	3529946	0.055	9.52	43I.OX.	371895	3521334	0.095	1.78	6A.	375049	3524531	0.393	4.32
7I.OX.	363608	3532904	0.223	14.06	44I.OX.	369057	3521122	0.048	2.51	7A.	378862	3528122	0.002	20.13
8I.OX.	387832	3526681	0.65	11.69	45I.OX.	370822	3518003	0.18	5.28	8A.	395150	3533552	0.185	16.18
9I.OX.	392117	3530556	2.39	3.43	46I.OX.	366282	3513264	0.42	12.66	9A.	400945	3520176	0.041	14.26
10I.OX.	396977	3531607	0.15	4.82	47I.OX.	361587	3513378	3.63	11.88	10A.	398581	3515329	0.029	6.5
11I.OX.	403472	3533331	2.289	0.5	48I.OX.	373808	3518503	0.18	1.73	11A.	402717	3510857	0.58	30.19
12I.OX.	405115	3532863	1.702	0.2	49I.OX.	377084	3516750	0.29	6.35	12A.	397622	3508969	0.654	0.57
13I.OX.	403842	3530690	3.338	3.25	50I.OX.	380569	3516723	0.061	2.23	13A.	393031	3519202	0.935	19.02
14I.OX.	403157	3524049	0.419	5.58	51I.OX.	377407	3532469	0.65	16.63	14A.	374222	3513207	1.385	13.78
15I.OX.	396382	3521024	0.53	48.15	52I.OX.	374576	3508986	0.21	4.29	15A.	370765	3519277	0.029	2.58
16I.OX.	368068	3507355	0.17	0.66	53I.OX.	369722	3512478	2.7	2.26	16A.	368890	3519004	0.335	5.56
17I.OX.	370055	3533974	0.24	15.4	54I.OX.	370152	3506353	0.71	4.29	17A.	365622	3516686	0.599	4.61
18I.OX.	388869	3522152	0.98	5.67	55I.OX.	364258	3507711	1.07	23.04	18A.	369901	3514767	0.314	9.86
19I.OX.	399565	3519156	1.246	3.85	56I.OX.	379357	3508162	0.251	3.77	19A.	375742	3520059	0.015	6.64
20I.OX.	397077	3517464	0.141	2.18	57I.OX.	383762	3507453	0.303	5.1	20A.	378262	3515996	0.002	8.2
21I.OX.	402972	3515811	0.3	32.03	58I.OX.	381877	3514883	0.37	3.3	21A.	369748	3509530	0.052	19.22
22I.OX.	392973	3513873	0.63	18.86	59I.OX.	372253	3500206	0.1	42.75	22A.	382413	3490483	0.391	146
23I.OX.	359977	3520325	0.612	3.77	60I.OX.	374446	3527897	0.12	3.44	23A.	375072	3506682	0.098	15.22
24I.OX.	396476	3509125	1.054	2.28	61I.OX.	363981	3496249	0.066	1.04	24A.	380919	3505444	0.432	27.53
25I.OX.	399105	3510100	0.131	0.83	62I.OX.	361927	3497958	0.99	0.56	25A.	364091	3496321	0.118	3.53
26I.OX.	387228	3518575	0.71	21.58	63I.OX.	365579	3489096	1.906	0.97	26A.	383041	3513556	0.804	3.72
27I.OX.	357422	3508123	0.26	3.37	64I.OX.	363635	3486888	0.046	1.32	27A.	401760	3502345	0.407	12.44
28I.OX.	382705	3516849	0.222	0.84	65I.OX.	401292	3502747	0.331	0.93	28A.	404078	3491326	0.59	4.98
29I.OX.	380454	3518468	0.32	2.64	66I.OX.	366217	3528765	0.58	1.3	Propylitic				
30I.OX.	381591	3523651	0.19	20.58	67I.OX.	396739	3489521	5.28	3.56	No.	X	Y	Distance (Km)	Area (km ²)
31I.OX.	377643	3525767	0.095	3.64	68I.OX.	378048	3495111	0.306	3.3	1 P.	365274	3535728	0.283	10.59
32I.OX.	374703	3526124	0.654	1.31	69I.OX.	383778	3499824	0.152	0.8	2 P.	382647	3532895	0.821	10.78
33I.OX.	372932	3525767	0.516	0.29	70I.OX.	398237	3513272	1.22	5.93	3 P.	404084	3531773	2.587	3.16
34I.OX.	370297	3526201	0.175	1.29	71I.OX.	375633	3517770	0.21	1.93	4 P.	403047	3516089	0.565	16.129
35I.OX.	367774	3526509	0.195	3.71	72I.OX.	399762	3530357	0.69	4.15	5 P.	39563	3519355	0.907	0.69
36I.OX.	364952	3531149	0.042	1.72	73I.OX.	395657	3527255	0.26	9.36	6 P.	376955	3516835	0.078	0.32
37I.OX.	362218	3525449	0.105	0.83	—	—	—	—	—	7 P.	382546	3513243	1.243	2.17
—	—	—	—	—	—	—	—	—	—	8 P.	384675	3486491	1.384	3.35
—	—	—	—	—	—	—	—	—	—	9 P.	369559	3490956	1.13	0.05
—	—	—	—	—	—	—	—	—	—	10 P.	388059	3518942	0.161	1.9

Table 2. The table shows the measurement results of semi-variogram and Ellipsoid anisotropy

Anisotropy area Geostatistic			
	Alteration		
Ellipsoid anisotropy components	Iron oxide	Argillic	Propylitic
Diagram type	Linear	Exponential	Exponential
Correlation	0.93	0.99	0.54
Anisotropy ratio	0.74	0.84	0.77
Nugget	0	0	0.1
Relative sill	23.5	432.5	0.57
Major axis direction	116.9	170	0.5
Minor axis direction	26.9	80	90.5
Major axis range (m)	13212	14142	67947
Minor axis range (m)	9715	11942	52401
Sill	23.5	274	0.45
Major axis range/Minor axis range (m)	1.36	1.184	1.3

Figure 9. Correlation and linear regression diagram between iron oxide (a), argillic (b) and propylitic alteration (c) areas with distance from basement faults.

Figure 10. Field photographs of the study area. (Final report of Gazestan, 2015) (a) View of dickite unit with the andesite part (Hematite with iron oxide). (b) Chlorite alteration in metasomatic rocks. (c) View of argillic alteration in metasomatism rhyolite rocks (include of illite, montmorillonite, dickite). (d) View of the hematite colonization in dacitic-rhyolitic unit. (e) View of quartz dioritic unit, secondary minerals contains calcite, muscovite, biotite, chlorite and opaque minerals. (f) View of pink sub volcanic dacitic unit in Dolostone unit. (g-i) Lineaments (master joints) with rose diagrams in different directions.

ment by the interpreted remote sensing imagery. The field photographs of the hydrothermally altered rocks are illustrated in Figure 10. Microscopic photographs and XRD analysis of the study areas are shown in Figure 11 and Table 3, respectively.

Conclusions

The use of remote sensing data in the early stages of mineral exploration proved highly successful in recognition of the hydrothermal alterations. Moreover, the airborne magnetic map is used for the iden-

tification of lineaments possibly corresponding to basement faults which are poorly visible in the field. The form of iron oxide primary alteration Follow up main faults (basement fault) trends, According to alignment of the direction of the major axis of Ellipsoid anisotropy with the basement fault directions. Therefore, the highest levels of propagation of alterations are in the direction of the Ellipsoid axis trend. Also, there are two ideal diagrams of primary iron oxide and secondary propylitic alterations for gaining the best result from correlation between the alteration area strike and the basement fault strike trend (NW-SE).

Argillic and propylitic alterations correspond to the observed base-

Figure 11. Microscopic photographs of samples from the study areas in transmitted (a, b, c, d, and f) and reflected light (e). (a) Banded iron oxide and chert (crossed nicols, after Mohseni and Aftabi, 2015). (b) Apatite 2 mineralization in relation to hydro minerals amphibole, chlorite and epidote (4×-crossed nicols) (Rajabzadeh et al., 2014). (c) late mineralization of calcite and quartz (10×-crossed nicols). Mt: magnetite, Hem: hematite, Ap 1: apatite 1, Ap 2: apatite 2, Ap 3: apatite 3, Amp: amphibole, Ep: epidote, Chl: chlorite, Qtz: carbonate (Rajabzadeh et al., 2014). (d) Apatite 1 mineralization in relation to iron oxide-rich cores (10×-crossed nicols) (Rajabzadeh et al., 2014). (e) Needle-shaped actinolite adjacent to phosphate mineralization (10×-crossed nicols). Mt: magnetite, Hem: hematite, Act: actinolite (Rajabzadeh et al., 2014). (f) Quartz small crystals and alkali-feldspar with secondary hydroxide in feldspar matrix in the Kuh-e-Siah rhyolites (crossed nicols) (Mohamadi et al., 2016).

ment fault strike (NW-SE) in magnetic map. This means that, at depth, faults structurally control the distribution of Fe mineralizations indi-

cated at the surface by the iron oxide alterations halos.

Table 3. The table shows the results of XRD analysis of 4 deposit contains of Esfordi (Rajabzadeh et al., 2014), Mishdovan (Namiranian and Kalantar, 2014), Choghart (Barani et al., 2011) and Gazestan deposits (Final report of Gazestan, 2015)

Esfordi deposit						
X	Y	Sample code	Sample type	Mane phase	Trace phase	Rare phase
370902	3516627	BH1	Rhyolite tuff near mineralization zone	Hydroxy-apatite, chlor-apatite	Albite, flogopite, quartz, pyrite, hematite, calcite, microcline boracite	Vitioritomite melanocerite
370527	3516425	BH2	Rhyodacite near tuff	Fluoro-apatite, carbonate-fluor apatite	Microcline, Fluoroapatite, orthoclase, sanidine, albite, quartz, hematite, elite	Parsonsite
371015	3516540	BH4	Dolerite dike with amphibole veins	Fluoro-apatite	Actinolite, pyroxene, chlorite, covelite, hematite, garnet, biotite	Parsonsite, monazite, tritomite
370554	3516599	BH6	Amphibolite near phosphate masses	Fluoro-apatite Chlor-apatite	Biotite, bornite, pyroxene, calcite, ferribergite, covelite, hematite, chlorite	Tritomite, monazite, vitiotite
370726	3516590	BH7	Carbonaceous rocks with silica and hematite veins	Chlor-apatite	Hematite, quartz, chlorite, calcite, bornite, fluorite, muscovite,	
Mishdovan deposit						
No. of specimen		XRD results				
1		Quartz, Muscovite, Klinochlore, Albite (ordered),Pyrophyllite				
2		Quartz, Albite, Muscovite, Clinochlore				
3		Quartz, Albite (calcian), Muscovite				
4		Quartz, Calcite, Kaolinite, Andradite, Muscovite, Anorthite				
5		(ordered)				
6		Quartz, Grossular, Muscovite, Kaolinite, Albite (calcian)				
7		Quartz, Muscovite, Staurolite, Albite (calcian), Clinochlore				
8		Quartz, Staurolite, Muscovite, Albite				
9		Quartz, Clinochlore, anorthite, muscovite, albite				
10		Quartz,Albite, Muscovite				
11		Halite, Quartz, Magnesio-Riebeckite, Albite, Muscovite, Thomsonite, Clinochlore				
12		Quartz, Albite, Muscovite, Chamosite				
13		Quartz, staurolite, muscovite, Clinochlore				
14		Quartz, Clinochlore, Muscovite				
15		Quartz, Muscovite, Phlogopite, Clinochlore				
16		Quartz, Muscovite, Augite, Staurolite, Anorthite				
17		Quartz, Muscovite, Bassanite, Staurolite, Gypsum, Albite				
18		Quartz, Muscovite, Clinochlore, AlbiteAz				
19		Quartz, Kyanite, Staurolite, Paragonite, Muscovite				
Choghart deposit						
XRD analysis			Chemical analysis			
Mineral name		%	compound		%	
Magnetite		64	Fe		68.02	
Hematit		35	FeO		14.72	
Quartz		1	P		0.092	
			S		0.017	

Table 3. (continued)

Gazestan deposit				
X	Y	Sample cod	Mineralization/Alltration/ unit	XRD results
400947	3502935	SH5-1A	Magnetite-Apatite Mineraliztion	magnetite, Hematite, calcite, Clino Chlor, goethite, Quartz, Albite, fluoro Apatite,
401332	3502859	SH5-3A	Magnetite-Apatite Mineraliztion	Magnetite, Hematite, Quartz, clino Chlor,
401415	3502790	SH5-4A	metasomatismes Rhyolite	clino Chlor, Quartz, calcite, Orthoclase, Illite, Magnetite, Albite
401060	3502867	SH5-2A	Argillic alteration in metasomatismes Rhyolite	Calcite, Quartz and Montmorillonite
401066	3503365	SH5-5A	Argillic alteration in metasomatismes Rhyolite	Quartz, Calcite, Moscovite, Albite, clino Chlor, Orthoclase
400485	3502796	SH5-6A	Volcanic dockite unit	Quartz, Hematite, Orthoclase, Moscovite, Iliite,
400554	3502885	SH5-7A	Metasomatismes Rhyolite	lino Chlor, Magnetite, Quartz, Albite, Hematite, Orthoclase
400691	3503073	SH5-8A	High intensity metasomatismes part	Quartz, Calcite, Moscovite, Albite, clino Chlor, Orthoclase
400620	3502450	SH5-9A	Iron oxide silisic alteration in dockite-Rhyodockite unit	Quartz, Orthoclase, Magnetite, Jarosite, Albite and Moscovite
400548	3502499	SH5-10A	Argillic alteration	Quartz, Orthoclase, Moscovite and dickite
401639	3502795	SH5-11A	metasomatismes Rhyolite	Clino Chlor, Magnetitet, Albite, Orthoclase, Hematite and Moscovite
400680	3502845	SH5-12A	metasomatismes Rhyolite	Clino Chlor, Magnetite, Quartz, Albite, Orthoclase and Moscovite
401464	3502706	SH5-13A	metasomatismes Rhyolite	Clino Chlor, Magnetite, Quartz, Albite, Orthoclase, Hematite, Moscovite and Tremolite
401088	3502765	SH5-14A	metasomatismes Rhyolite	Clino Chlor, Magnetite, Orthoclase, Quartz, Albite, Dickite, Biotite
400668	3502820	SH5-15A	metasomatismes Rhyolite	Clino Chlor, Quartz, Magnetite, Albite, Illite, Orthoclase, Moscovite

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