INTEGRATED ANALYSIS OF REMOTE SENSING, AEROMAGNETIC, GEOLOGICAL AND MINERAL OCCURRENCE DATA FOR THE ASSESSMENT OF A SUBDUCTION SETTING ALONG THE ZAGROS OROGENIC BELT OF IRAN

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ABSTRACT

The formation of Zagros Orogenic Belt of Iran, extending over 2000 km along the NW-SE direction, has been subjected to considerable controversy. Several geologists believe that this belt has been resulted by the subduction of Afro-Arabian plate underneath of the Iranian plate. This study presents an integrated analysis of remote sensing, geological and mineral occurrence data within a country scale GIS to test the hypothesis of subduction along this belt and to identify more precisely the subduction features inferred earlier by geologists. The interpretation of aeromagnetic data identifies several elongated subsurface ophiolitic rocks, which are believed to be the remnants of Neo-Thetys ocean that existed between the Afro-Arabian plate and Iran plate. Three sets of major NW, NE and N-S trending structures were identified by the processed aeromagnetic and AVHHR imagery. These structures control the occurrence of porphyry copper and epithermal precious metal mineralizations. Integrated analysis of all the available data presents a final map showing different elements of the subduction setting along the Zagros Orogenic belt. This study indicates that the suture zone, the surface expression of subducting Afro-Arabian plate beneath the Iran plate, is not located along the main Zagros thrust zone, as traditionally accepted by several geologists. It is inferred that the suture zone occurred at the southwestern boundary of the Urumieh-Dokhtar volcanic arc.

1 INTRODUCTION

The Zagros Orogenic Belt (ZOB) in Iran extends over 2000 km in a NW-SE direction from the Eastern Anatolian Fault of eastern Turkey to the Oman Line in southern Iran (Alavi, 1994). It is part of the Alpine-Himalayan orogenic and metalogenic belt. Its mineral potential, across the Alpine arc, from Italy through the Balkan, Turkey, Iran and Pakistan, is demonstrated by frequent presence of porphyry copper, volcanogenic massive sulphide and hydrothermal Pb, Zn, Ba-deposits and numerous occurrences of As, Sb, Hg (Au, Ag) related to epithermal systems connected to ensialic Andean arc-type volcanism (Pirajno, 1992).

There exists controversy among geologists about the tectonic setting and formation of the ZOB. Both a subduction model and a continental rifting model have been proposed. Among those who support the subduction model there is disagreement regarding certain spatial features and elements typical of a subduction setting such as the precise location of the suture zone – with ophiolites – and its position *vis-a-vis* the magmatic arc (Alavi, 1980, 1994; Takin, 1972 and Berberian and King, 1981).

The subduction-related setting of the ZOB is believed to be associated with the closure of the Tethys ocean according to the following scenario: early Mesozoic separation of a small continental block – the Central Iranian Block – from the rest of the Gondwana landmass followed by a NE subduction of the newly generated Neo-Tethyan oceanic crust below the Iranian micro-continent and subsequent collision between the Afro-Arabian and Iranian plates (Alavi, 1994).

Although to date different parts of the ZOB have been subjected to detailed structural-metamorphic-magmatic studies, a synthesis of the geodynamic history of the entire belt is still far from complete. In this paper a contribution is being made in presenting an integrated analysis of aeromagnetic, AVHRR imagery, geological and mineral occurrence data, within a country-scale GIS framework. This furthermore enables us to test the hypothesis of the subduction versus continental rifting model of the ZOB. Attempts are being made to identify features that are related to the NE subduction of the Afro-Arabian plate beneath the Iranian plate. Subsequently, closure of the oceanic basin and plate collision resulted in southwestward transport and stacking of passive margin, accretion wedge and suture material – e.g. ophiolite fragments – leading to significant crustal thickening. Finally, intramontane basins formed by orogenic collapse of the thickened lithospheric crust. The formation of the ZOB is thus the result of a complex geodynamic scenario. This, in turn, defines the metallogenetic scenario and the role of the ZOB on the regional setting of porphyry copper and related epithermal mineralizations.

2 GEOLOGICAL SETTING OF ZAGROS OROGENIC BELT

Since the pioneer work of Schröder (1944) and Stocklin (1968) the ZOB has always been divided into different tectono-metamorphic-magmatic domains. In this paper we follow the generally accepted sub-division by Alavi (1994). He distinguishes three elongated parallel zones, i.e., from NE to SW, (1) the Urumieh-Dokhtar Magmatic Assemblage (UDMA), (2) the Sanandaj-Sirjan Zone (SSZ) and (3) the Zagros Simply Folded Belt (ZSFB) (Fig. 1). Alavi (1994) further postulates that the boundary between the UDMA and SSZ is formed by the Zagros Suture (ZS) characterized by some elongated, mylonitized and sheared ophiolite bodies. It represents the suture zone between the Afro-Arabian plate and the Iranian plate. The boundary between the SSZ and ZSFB is formed by the so-called Main Zagros Thrust (MZT). The intensely sheared and thrusted zone in front of the MZT is called the Zagros Thrust Zone (ZTZ; c.f. Stocklin, 1968). This zones grades into the lesser-deformed ZSFB and eventually into the undeformed sediments of the Mesopotamian-Persian Golf basin.

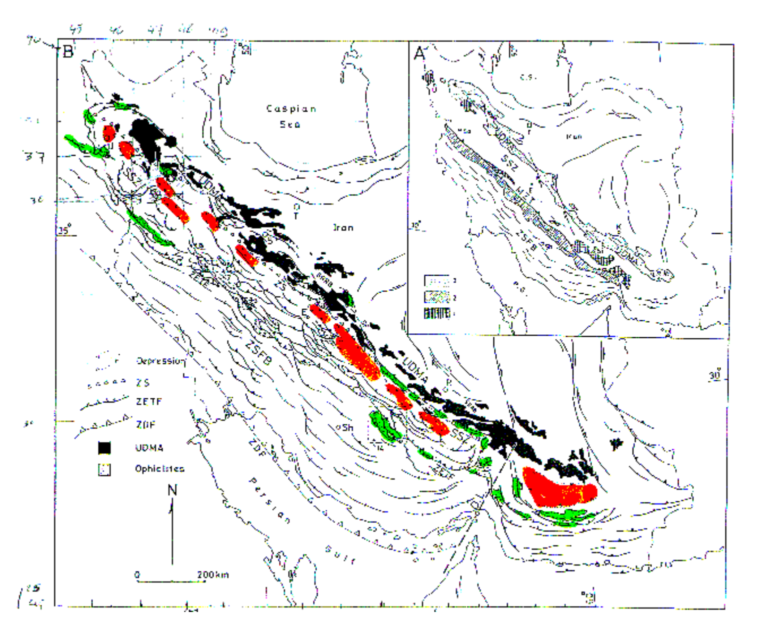

Figure 1. (A) Zagros subdivision according to Stocklin (1968). 1 = Precambrian basement; 2 = Zagros thrust zone; 3 = Urumieh-Dokhtar Magmatic Assemblage (arc). (B) Main structural elements of the Zagros belt. Abbreviation: T = Tehran; U = Urumieh; Sh = Shihraz; UDMA= Urumieh-Dokhtar Magmatic Assemblages; MZT = Main Zagro Thrust; SSZ= Sanandaj-Sirjan Zone; ZSFB = Zagros Simply Folded Belt; ZDF = Zagros deformation front; ZETF = zagros exposed thrust front, ZS = Zagros Sature and O.L. = Oman line.

UDMA arc = black
Ophiolites = green
Depression = red

2.1 Urumieh-Dokhtar Magmatic Assemblage

The Urumieh Dokhtar Magmatic Assemblage (UDMA or Urumieh-Dokhtar Zone *sensu* Schröder, 1944) comprises of a linear magmatic belt, which extends along the entire length of the ZOB. Major plutonic rock types in this zone comprise diorite, granodiorite, gabbro and granitoids. Volcanic rocks occur widespread as flows of trachy-basaltic (locally shoshonitic), andesitic and dacitic composition. Other volcanic product include agglomerates, ignimbrites and tuffs (Alavi, 1980). Petrographic data suggests a generally calc-alkaline composition. Granitoid rocks of the UDMA are tentatively classified as calc-alkaline I-type Cordilleran-type products. Geological evidence indicate a post-Upper Jurassic to pre-Lower Cretaceous age of emplacement for the oldest plutons (Nabavi, 1972). Magmatic activity peaked during the Eocene as manifested by the interlayering of large volumes of volcanic material and numulitic limestones. The youngest magmatic products comprise volcanic flows and pyroclastics of Quaternary age.

The UDMA coincides with a negative Bouguer gravity anomaly of –150 mGal, indicating a continental crustal thickness of 45-50 km, some 5-10 km thicker than the crustal average of the Iranian lithospheric plate. NE-directed thrusting affected parts of the magmatic belt in the Tertiary.

2.2 Sanandaj-Sirjan Zone

The Sanandaj-Sirjan Zone (SSZ) is located to the southwest of the UDMA and has a width of 150-250 km. Its southwestern boundary is formed by the parallel Main Zagros Thrust (MZT) and Zagros Thrust Zone (ZTZ) from Sanandaj in the northwest to Sirjan in the southeast. It joins the Taurus orogenic belt in Turkey.

The combination of sedimentary and igneous rocks as described above indicate a prolonged history of intermittent crustal extension which started in the Carboniferous and probably culminated in the Jurassic when the Iranian plate broke away from the Afro-Arabian plate. Each phase of crustal extension resulted in crustal thinning, basaltic underplating and an increased heat flow. This, in turn, gave rise to limited bi-modal magmatism. Some of the Paleozoic and Mesozoic rocks in the SSZ have been affected by low- to medium-grade greenschist facies metamorphism (Alavi, 1994). Thermal events during the Late Cretaceous and Middle to Late Triassic even reached medium- to high-grade greenschist facies conditions (e.g., Sabzehi, 1992). The latter event coincided with an important phase of bi-modal magmatism. The metamorphic events may reflect the combined results of increased heat flow and detachment faulting.

A series of elongated depressions mark the northeastern boundary of the SSZ. Towards the southwest the SSZ shows a strong increase in elevation, associated with a negative Bouguer anomaly. From this the depth to the Moho can be calculated (Dehghani and Markis, 1983). It appears that from NE to SW crustal thickness of the SSZ increases from an average of ~ 40 km to ~ 55 km.

Alavi (1994) presents a number of examples all demonstrating that the increase in crustal thickness is caused by overthrusting and stacking of napes, an idea he already proposed in an earlier publication (Alavi, 1980). A number of areas have been described by Alavi (1994) in detail (e.g., the Kuhrang, Chaghagorg, Nahavand, Malayer, Asadabad, Baft and Nayriz areas). A synthesis of the structural data from these areas indicate the SSZ is characterized by numerous thrusts masses that have been transported from NE to SW in a piggy-back style forming small- and large-scale duplex and imbricate structures. Older duplex structures have been truncated and overthrusted by younger duplex and imprecation structures giving rise to complex geometries. In places thrust masses of older rocks overly younger rocks. All structural elements – low-angle thrust planes, verging of drag folds and slicken-slides – demonstrate tectonic transport towards the southwest.

Ophiolites are particularly abundant along the NE and SW contact of the SSZ. Along the southwestern boundary ophiolites form an intricate part of the low-angle, southwest-verging thrust structures. Especially serpentinites may act as lubricants between thrust masses. Along the NE contact ophiolites are found of complexes bounded by steep, high-angle faults (Fig. 1).

2.3 Zagros Simply Folded Belt

The Zagros Simply Folded Belt is a fold belt characterized by NW-SE trending parallel anticlines and synclines. It consists of a thick pile of sediments overlying a high-grade metamorphic Precambrian basement. This basement is most probably an extension of the Neo-Proterozoic Arabian-Nubian Shield (a special geodynamic domain of the Afro-Arabian plate), which dips with a low angle in a north-eastern-ward direction below the Persian Gulf-Mesopotamian basin and the Zagros Simply Folded Belt (Berberian et al., 1982). According to Giesses et al. (1983) the Arabian-Nubian Shield even extends north-east-ward below the Sanandaj-Sirjan Zone.

According to Alavi (1994), the sedimentary cover sequence is 6 to 10 km thick and comprises of three main sub-units: (1) a latest Precambrian to earliest Cambrian evaporate-dolomite unit which is overlain discontinuously by a sequence of shallow (epi-) continental shelf siliciclastic and carbonate rocks of Cambrian to Carboniferous age, generally similar to the time-equivalent rock successions of the SSZ, (2) a succession of Carbonferous/Permian to Late Cretaceous continental shelf/platform carbonates and (3) a sequence of uppermost Cretaceous to Recent marine and non-marine carbonates and siliciclastics which show a pronounced southwestward migration of the depocentres through time (Koop and Stoneley, 1982). Fragments of the underlying basement are known from ‘exotic’ blocks in salt diapirs.

Traditionally, the Main Zagros Thrust (MZT) was considered as the boundary between the ZSFB and the SSZ. Its association with the Zagros Thrust Zone (ZTZ) – a narrow zone of extreme deformation, 10 to 70 km in width – and the occurrence of numerous ophiolite complexes in this zone prompted many geologists to consider the MZT as the suture between the Afro-Arabian and Iranian plates (e.g., Takin, 1972; Berberian and King, 1981; Berberian et al., 1982). From recent structural field observations and Stratigraphic correlation no sharp boundary between the ZSPB and the SSZ can be defined (Alavi, 1994).

3 COUNTRY-SCALE GIS

3.1 GIS Data Inputs

Geology (e.g., lithological and structural attributes) and mineral occurrences (e.g., deposit type, deposit name, UTM coordinates, major commodities and size) have been digitized from two 1:1 000 000-scale map sheets covering the whole ZOB. A Very High Resolution Radiometric (AVHRR) satellite image, comprising two reflective bands, two thermal bands and one intermediate band with a 1000x1000 m pixel size covering the whole of Iran, have been calibrated and geometrically corrected for further processing and interpretation. The AVHRR Utilities of ENVI software were used to read and display information from the AVHRR header, to calibrate the data to percent reflectance and brightness temperature and to use information in the data for georeferencing. Bands 1 and 2 were calibrated to percent reflectance and bands 3, 4, and 5 were calibrated to brightness temperature, in degrees Kelvin. A Polyconic projection was used to georeference the images.

Magnetic data from the nation-wide airborne reconnaissance survey (7.5-km line spacing), conducted in 1976, was recently digitized from total magnetic contour maps. State of the art visualization and enhancement techniques have been applied to the data set for interpretation.

Finally, all data sets were re-formatted to a uniform map projection (Lat-Long coordinates) and combined to create a database and GIS of the whole ZOB.

3.2 Processing and Interpretation of AVHRR Imagery

Several colour composite combinations of processed AVHRR bands were created to identify different geological features along the ZOB. A colour composite combination of two thermal bands (bands 4 and 3) and the intermediate reflective-thermal band (band 2) proved to be the best image for lithological and structural mapping. The three parallel geologic domains that subdivide the ZOB, extending in a NW-SE direction over 1750 Km across much of Iran, show different spectral characteristic in this image. The UDMA, SSZ and ZSFB are characterized by dark blue, yellow and a mixture of yellow and light blue, respectively. By overlaying the previously mapped volcanic rocks of the UDMA on this image, some additional exposures of volcanic rocks, located along the axes of the known magmatic arc, were mapped. The boundary between the SSZ and UDMA is clearly visible in this image. The image also highlights several sharply defined parallel-elongated structures along the Zagros Thrust Zone ((Fig. 2).

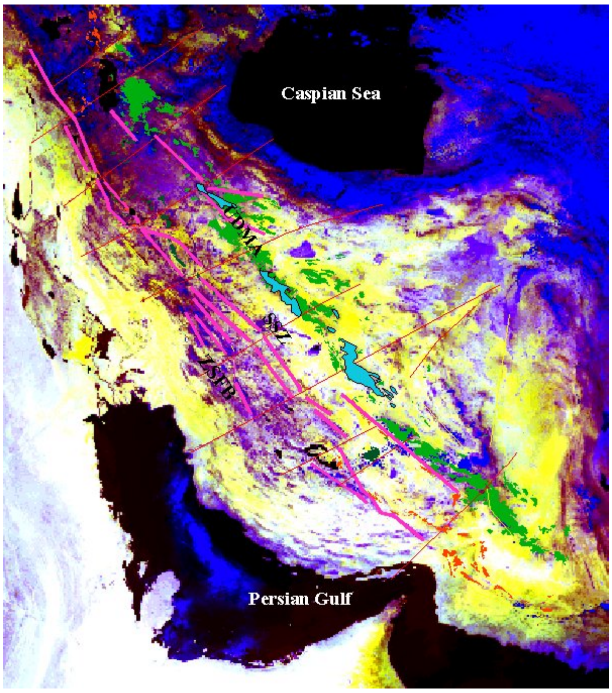

Figure 2. Colour composite AVHRR image (bands 4,3 and 2) with the overlaid maps of interpreted major faults, trending in a NW-SE (purple lines) and in NE-SW (red lines), and the interpreted magmatic rocks of UDMA arc (blue) along the axes of known magmatic rocks (green).

A principal component transformation (PC) has been applied to the five bands of the AVHRR imagery in order to highlight additional structural features. Two sets of lineaments, one trending in a NW-SE and the other in a NE-SW direction, were identified from the PC1 image by applying directional filtering. The alignments of relatively shorter lineaments were used to interpret several major structures running in NW-SE and NE-SW directions (Fig. 3). It appears that the NW-SE trending structures, particularly along the Main Zagros Fault (MZF), have been locally displaced by the NE-SW structures extending into the SSZ and UDMA.

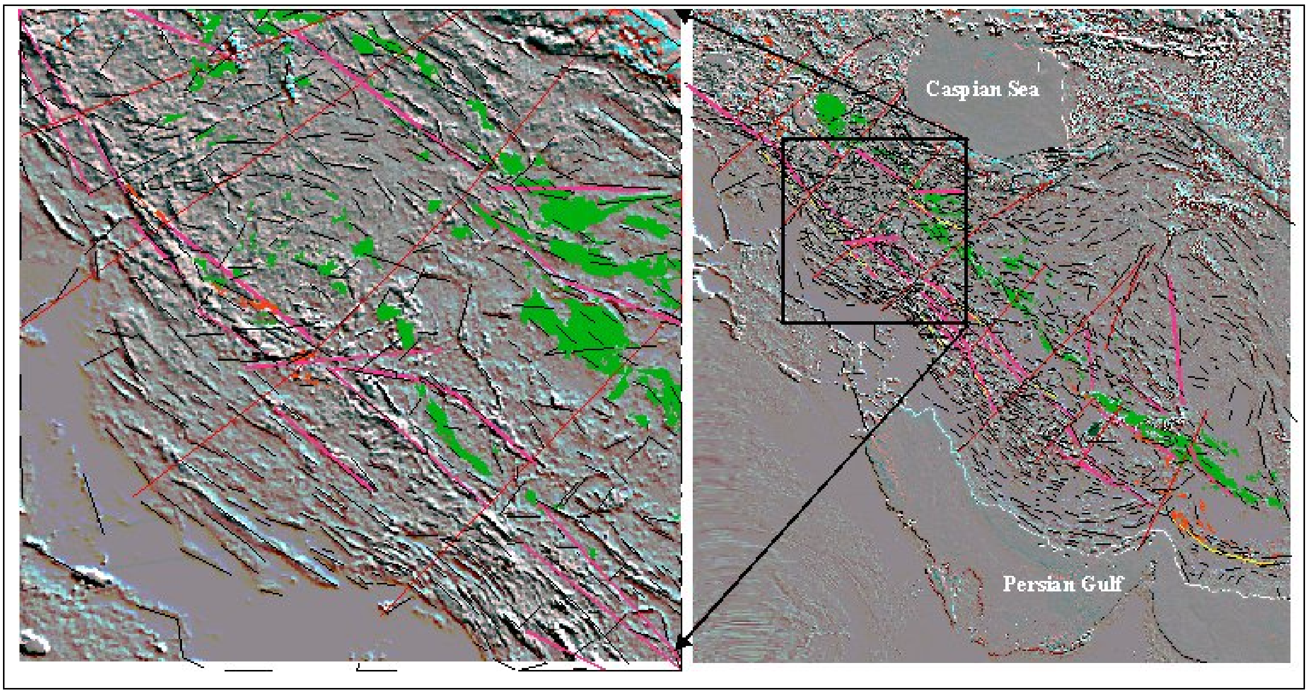

Figure 3. The map in left is a principal components image (PC1) overlain with the interpreted linear structures and the known volcanic rocks of UDMA arc (green) and known ophiolites (red), the map in right is the enlarged northwestern part of right map as indicated by black box.

By combining the new geological information derived from the processed colour composite and PC1 images, the boundaries of the three parallel zones of ZOB were identified more precisely. Next, this has been integrated with the aeromagnetic, geological and mineral occurrence data.

3.3 Processing and Interpretation of Aeromagnetic Data

Most rock types have specific magnetic susceptibilities and therefore aeromagnetic measurements, when suitably processed, can reveal rock types and structures. Especially certain igneous rocks that are relatively rich in magnetite (e.g., serpentinites and other igneous rocks) will be highlighted. In case non-magnetic rocks overly magnetic rocks, the depth to the magnetic source can be calculated using Euler deconvolution. Colored and grey scale shaded relief images of the total magnetic field are useful for litho-structural mapping. Analytical signal analysis of the total magnetic field is used to identify strong magnetic anomalies associated with highly magnetic susceptible generally igneous rocks, both outcropping and at depth. Paterson and Reeves (1985) point out that analytical signal analysis is often used for mineral exploration because magnetic information is displayed in a more interpretable manner than total magnetic intensity: Anomalies correlate directly with causative bodies and are positioned symmetrically over them. The analytical signal is independent of the inclination of the magnetic field; this has advantages over reduction to the pole in that the direction of magnetization does not need to be known (Qin, 1994).

In the case of the ZOB, aeromagnetic data is processed to yield maps of inverted grey scale total magnetic field, shaded analytical signal, grey scale 2nd vertical derivative and depth to the magnetic sources.

Figure 4 is an inverted grey scale total magnetic field map of Iran in which high amplitude magnetic anomalies appear as intense dark colour. This map was used to identify NW-SE, NE-SW and N-S linear features. The NW-SE structures are mainly spatially associated with the Main Zagros thrust fault and locally extend into the SSZ. The boundary of SSZ and UDMA is also marked by these structures. Two sets of NE-SW and N-S conjugate faults were also interpreted from this map. The conjugate faults appear to postdate the NW-SE structures. These two sets of structures displaced both the NW-SE structures as well as the magmatic rocks along UDMA arc.

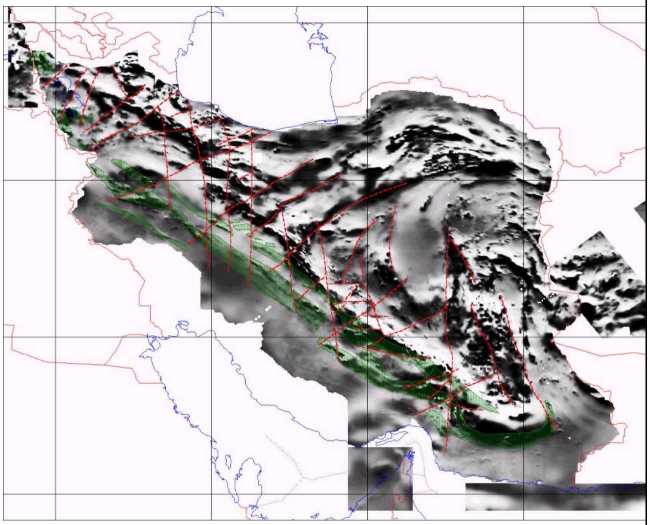

Figure 4. Inverted grey scale map of total magnetic field showing the linear structures, the red lines are interpreted NE-SW and N-S conjugate faults, the NW-SE linear features are shown in green.

Figure 5 is a shaded relief analytical signal map of Iran in which anomalously high amplitude signals appear in pink. The strongest anomalies extend in a NW-SE direction and coincide with the UDMA magmatic arc. These anomalies mainly arise from the outcropping and sub-cropping igneous rocks. The igneous rocks in this region are the surface and shallow volcanics of mainly andesitic composition and the intermediate to deep intrusives of generally granodioritic composition. By overlaying the previously mapped outcropping igneous rocks of UDMA on this image, several other surface and subsurface igneous rocks were mapped along this structural axis.

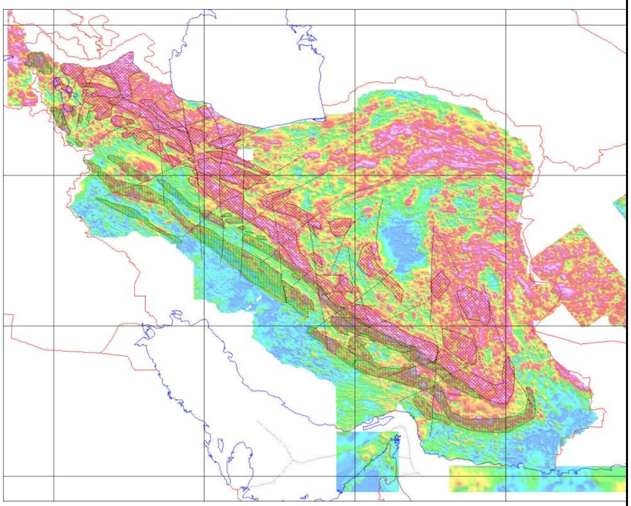

Figure 5. Analytical signal map of Iran showing the high amplitude analytical signal anomalies extending in a NW-SE direction as purple shade, which are mainly associated with UDMA arc and ophiolites as indicated as red hatches and green hatches, respectively, on the map.

In addition, the magnetic signatures, characterizing the exposed ophiolites of the ZOB, were also used to map some unrecognized linear elongated ophiolite bodies both at surface and at depth (Fig. 4). The ophiolitic rocks are characterized by narrow elongated medium-high magnetic anomalies which extend along NW-SE linear structures.

3.4 Data Integration

The results obtained from the interpretation of aeromagnetic data and AVHRR imagery were integrated with the geological, mineral occurrence and digital elevation data of Iran. The structures have been digitized from processed AVHRR and aeromagnetic images and converted to suitable formats for data integration. The UDMA magmatic arc of the ZOB was also remapped from the processed AVHRR and magnetic images. The magnetic images assisted in the recognition of some of the sub-cropping igneous rocks along the volcanic-arc and also sub-cropping ophiolite sheets along the Main Zagros Thrust (MZT) which extend into the Sanandaj-Sirjan zone. This information was integrated with the existing geological, mineral occurrence and digital elevation data to test the subduction hypothesis in the ZOB.

Several elements of a subduction-related setting have been identified and the boundaries of the three tectono-magmatic domains of the ZOB have been remapped with a much higher accuracy using an integrated analysis of AVHRR, aeromagnetic, geological and mineral occurrence data (Fig. 6). The results confirm the presence of a subduction zone along the ZOB and the occurrence of the suture zone along the boundary of UDMA arc and SSZ, as originally suggested by Alavi (1994). Our interpretation is based on the following evidences.

The three parallel tectono-magmatic domains of ZOB are clearly distinguishable in aeromagnetic and AVHRR imagery data.

Interpretation of aeromagnetic data indicates the presence of many parallel linear subcropping ophiolitic rocks, characterized by intermediate-strong positive magnetic anomalies, along the Main Zagros thrust fault, which also locally extend into the SSZ zone. None of these linear structures can be singled out as the main suture zone between Iranian plate and Afro-Arabian plate as originally suggested by several geologist mentioned earlier. Most of the interpreted ophiolites do not coincide with the Main Zagros thrust fault.

Very strong magnetic anomalies along the UDMA arc may arise from a combination of volcano-plutonic rocks and subducting slabs of Neo-Thetys oceanic crust beneath the UDMA arc. The presence of outcropping elongated ophiolitic rocks, which show a very strong positive magnetic anomalies, at the contact of SSZ and UDMA in the SW and NW of the ZOB. Outcropping ophiolites on the southern edge of the UDMA can be magnetically traced into the SSZ at depth; this could indicate that the remnants of oceanic crust have been moved from their original place toward the SW by reverse faulting as suggested by Alavi (1994).

Three interpreted sets of NW-SE, N-S and NE-SW trending faults are integrated elements of ZOB. The NW-SE trending structures are mainly located on the SSZ and ZSFB, while the other two sets appear as conjugates which crosscut the UDMA, SSZ, ZSFB as well as the NW-SE trending structures.

The distribution of most mineral deposits (in particular porphyry copper deposits in the SW of the Urumieh Dokhtar arc and epithermal gold deposits in the NW of the arc), are spatially associated with some of the subduction elements, such as the volcanic arc and ophiolites, and controlled by major NW-SE trending structures which are crosscut and off-set by equally prominent NE-SW and N-S trending faults. The porphyry copper deposits are spatially associated with NW-SE trending structure and UDMA magmatic rocks, while, the epithermal mineralization, in particular those of NW Iran, are associated with NE-SE and N-S trending faults. The NW-SE structures interpreted as compressional faults associated with subduction and the NE-SW and N-S structures are interpreted as extensional conjugate faults formed by orogenic collapse due to the reverse faulting and thickening of the crust after or during the subduction activities.

4 A SUBDUCTION MODEL FOR THE ZOB

As mentioned earlier, there are two models for the occurrence of subduction along the ZOB in Iran. The first model indicates that the suture between and Afro-Arabian plate and Iranian plate is located at the MZT, while the second model argues the occurrence of the suture at boundary UDMA and SSZ. This present study confirms the subduction model with the occurrence of the suture along the contact of UDMA and SSZ.

Based on the published data and the new interpretations described above and presented in an integrated map (Fig.6), we conclude the following scenario for the ZOB.

1- Opening of the Paleo-Tethys Ocean (Permo-Triassic);
2- Opening of Neo-Tethys, the Iranian plate by breaking away from Afro-Arabia, peak in bi-modal magmatism;
3- Subduction of the Neo-Tethys Ocean beneath the Iranian plate, creation of magmatic arc which is spatially associated with porphyry copper mineralization.
4- Continent-continent collision (timing?), resulting in SW-directed thrusting of accretion wedge and passive margin sediments and suture ophiolite (underlying basement shortened making use of original listric and detachment fault by back-trusting and reverse faulting), and folding of ZSFB cover(underlying basement thrusts underneath SSZ and possibly UDMA)
5- Orogenic collapse of thickened crust, together with bi-modal magmatism (mainly rhyolites, tuffs and basalt) and NE-SE and N-S extensional faulting, in particular in the NW of Iran, which control the precious metal epithermal mineralization

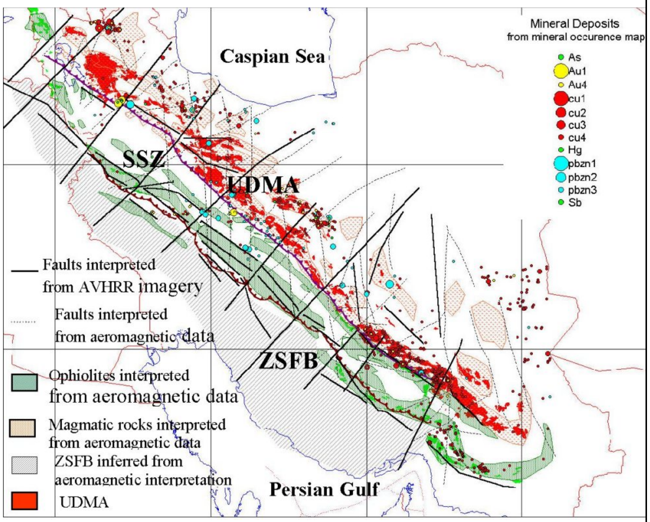

Figure 6. Map showing different elements of ZOB based on integration of the results obtained from AVHRR imagery, aeromagnetic, geological and mineral occurrence data.

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