Structural Control on Banded Iron Formation (BIF) and Gold Mineralization at Abu Marawat Area, Central Eastern Desert, Egypt

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Abstract. Abu Marawat area is considered as a promising site for exploration of gold mineralization, where many ancient gold mines, hydrothermal alteration zones, and intervening quartz veins are present. This study is a field-based structural analysis that aims at revealing the relationship between mineral occurrences and local structural setting. The area is a part of a back-arc volcanosedimentary sequence associated with banded iron formation (BIF) that has undergone extensive ductile and brittle deformation history. This multiple deformation is manifested by four phases. D_1 and D_2 are the product of compressional stresses and are expressed by F_1 , F_2 and F_3 folds in low-grade regionally metamorphosed rocks. D_1 was a progressive deformational phase started with F_1 folds, which in a later stage were overprinted by F_2 folds. It resulted from NW-SE-oriented pure shear and is associated with imbricate thrust stacks, which control the locations of listwanite bearing gold. NE-SW-oriented compressive stress during D_2 is displayed by F_3 -slip folds at the early stage followed by N-S- to NW-trending dip-slip normal faults and related shear zones. Mineralized quartz veins (MQV) were developed post- D_2 and pre- D_3 . Folding and refolding in addition to thrust movement play a significant role in shortening and thickening of the iron formation bands located at the summit of Gebel Abu Marawat. D_3 and D_4 are expressed by brittle deformation. D_3 is displayed by conjugate shear planes represented by sinistral-NW-oriented and dextral-NE-oriented strike-slip faults that led to the dislocation and redistribution of gold mineralization associated with both MQV and listwanite. Barren quartz veins trending E-W were also developed along gash fractures formed during this phase of deformation. Finally,

D₄ represents an extensional period that affected the study area and is manifested by N-S- to NNE-oriented normal dip-slip faults.

The present study has immense significance for gold exploration in providing the essential background to understand the structural elements controlling BIF and gold mineralization. An open pit mine for iron and gold on the eastern slopes of Gebel Abu Marawat is recommended.

Keywords: Abu Marawat, Eastern Desert, BIF, Gold mineralization, Gossans, listwanites, Shear zone, Structural analysis.

Introduction

Since the last Century the exploration for gold deposits as well as BIF in the eastern desert of Egypt has achieved a great progress. Many studies have been done based on mode of occurrences, classifications, type, and geochemical nature of mineral deposits. In spite of their primitive technology, most of the 96 well-known gold occurrences and deposits (Kochine and Bassuni, 1968) were exploited by ancient Egyptians since the pre-dynastic time. The systematic study of the mineral deposits of Egypt began in the past century with the pioneering work of Hume (1937) who made a comprehensive list of mineral occurrences in association with the Precambrian rocks, with notes on stratigraphy, mode of occurrences, and genesis of some deposits.

Mineral deposits of the Eastern Desert were classified by Amin (1955) into seven groups; six of them are of Precambrian age, while the last one includes those of Miocene and younger ages. El Shazly (1957) classified the mineral deposits of Egypt, on the basis of time relations and their mode of formation, into Precambrian, Cretaceous, Miocene and Pleistocene to Recent deposits, with a further classification of the Precambrian group into early and late subgroups. Kochine and Bassuni (1968) classified gold deposits according to the mode of occurrence and the nature of mineralization into three types: dike, vein, and placer types. Sabet and Bordonosov (1984) classified gold deposits in Egypt into three formations: gold-sulfide formation, skarn, gold-ferruginous quartzite formation, and gold quartz formation.

Gold is also found along with some other ore deposits in some Algoma-type banded iron formation (Sims and James, 1984) and in the alteration zones (Botros, 2002). Based on the above observations and the recent crustal evolution models suggested for the evolution of the Nubian

shield that implies collision of island-arcs and micro-continents through subduction processes (Stern, 1994; and Kusky *et al.*, 2003), Botros (2004) has classified the gold deposits in Egypt into: (1) Stratabound deposits hosted in island-arc volcanics and volcanoclastic rocks which include gold-bearing Algoma-type banded iron formation, gold-bearing tuffaceous sediments and gold-bearing volcanogenic massive sulfide deposits. (2) Non-stratabound deposits hosted in both igneous and metamorphic rocks which include the vein-type mineralization, and disseminated-type mineralization hosted in the hydrothermally altered rocks that have recently become the main target for gold exploration. And (3) placer gold deposits which include the modern and the lithified placers.

BIF are of economic interest as they host the world's largest iron ore deposits and many gold deposits. Fourteen occurrences of BIF have been located, mostly in the central Eastern Desert (Fig. 1). Similar to the iron ores of Archaean and younger volcanic terranes, the Egyptian iron formations are linked in time and space to volcanic activity (Sims and James, 1984; El Habaak and Soliman, 1999; and Basta *et al.*, 2000).

Abu Marawat area (26°26' to 26°33'N, 33°35' to 33° 42' E) is known as an Algoma-type BIF in the northernmost part of the central Eastern Desert of Egypt. The presence of ancient mine workings associated with the BIF has attracted several authors to do geochemical exploration for gold in the Abu Marawat area (*e.g.* Abdel Tawab and Zaki, 1987; Dardir and El Shimi, 1992; Hassanein, 1994; El-Mezayen *et al.*, 1995; and Zoheir and Akawy, 2009). In association with Russian geological teams, the Egyptian Geological Survey and Mining Authority (EGSMA, 1992) carried out a preliminary geochemical exploration program at the Abu Marawat area and reported several zones of geochemical anomalies/hydrothermal alteration potential for gold (Armanious, 1969; Sabet *et al.*, 1976; Sabet and Bondonosov, 1984; Zaki *et al.*, 1987; David, 1988; and Botros, 1993). MINEX Minerals, a subsidiary of U.K. Greenwich Resources Plc, carried out a percussion and diamond drilling program in Abu Marawat area, led to the identification of gold anomalies in two elongate, parallel zones (140 and 230m long, and 5-10m wide, respectively) of brecciated volcanic/volcanoclastic rocks and quartz stockwork (David, 1988). EldougDoug (1990) mapped five alteration zones at the Abu Marawat area, in which

assay data indicated gold concentrations ranging from traces up to 12 g/t Au in the intensively silicified volcanoclastic rocks.

The purpose of the present study is to understand the structural parameters which control the distribution and concentration of gold and BIF at Abu Marawat area. Detailed mapping of quartz veins, BIF, alteration/gossan, and shear zone sites were also carried out during the course of this study.

Fig. 1. Location map showing the distribution of BIF and massive sulphide deposits in the Eastern Desert of Egypt. Inset map shows gold occurrences nearby the Abu Marawat area (compiled from Kochne and Bassuni, 1968).

Regional Geological Setting

The Arabian-Nubian Shield (ANS), an exposure of Precambrian rocks on the flanks of the Red Sea, that has been controlled by plate collisions associated with the Pan-African event that ended 615- 600Ma ago (Kröner *et al.*, 1992). ANS forms the suture between East and West Gondwana at the northern end of the East African Orogen (EAO). Subduction, starting c. 870 Ma, and initial arc-arc convergence and terrane suturing at c. 780 Ma, marked the beginning of ocean-basin closure and Gondwana assembly (*e.g.* Stern and Hedge, 1985). Terrane amalgamation continued until c. 600 Ma, resulting in the juxtaposition of East and West Gondwana across the deformed rocks of the shield, and final assembly of Gondwana was achieved by c. 550 Ma following overlapping periods of basin formation, rifting, compression, strike-slip faulting, and the creation of gneiss domes in association with extension and/or thrusting (Johnson and Woldehaimanot, 2003).

The exposed basement rocks of Egypt are represented by the northernmost part of the Nubian Shield that is located to the east of the Nile Valley and the Oweinat area in the western most part of Egypt. It is composed of NW-SE trending allochthonous ophiolitic and volcanoclastic assemblages at greenschist facies, and is extensively intruded by alkaline granitic batholiths and mafic plutons (El-Nisr *et al.*, 2001; and Farahat *et al.*, 2007). These assemblages are overlain by molasse-type sediments that have been deposited during the late stages of the EAO and intruded by calc-alkaline granites with extensional dike swarms indicating transition from subduction through collision and extension after the formation of a juvenile continental crust at about 550 Ma (Vail 1985; and Greiling *et al.*, 1994).

Local Geological Setting

Abu Marawat area is a part of back-arc basin and is composed of a volcanosedimentary sequence associated with BIF (Fig. 2, 3A). Calc-alkaline metavolcanic rocks, showing greenschist facies regional metamorphism, range from mafic to felsic and from massive to sheared. The main rocks are intermediate lava flows and pyroclastics. Metavolcanics are overlaid by immature to semi-mature conglomerate, greywacke, and siltstone of the Hammamat Group (Fig. 2). Slices of altered, strongly foliated (180°, 70°W) ultramafic rocks (dominated by

talc-carbonate with relic cores of antigorite after olivine) represent occluded ophiolitic oceanic crust (ophiolitic mélange) (Fig. 3A). They are recorded at the northeastern part of the mapped area (Fig. 2) and form N-S-oriented belt of allochthonous, tectonized serpentinite and related listwanite blocks embedded in strongly ductile sheared matrix. They are thrust over metavolcaniclastic rocks (Fig. 2, 3B). Meta-andesites are predominating in the eastern and northern part of the area, whereas latite and rhyolite occur in the middle. The basic metavolcanics and related tuffaceous units are outcropped mainly at the southwestern part of the mapped area. They are neither altered nor sheared. Whereas the central parts of the mapped area are dominated by altered and sheared metavolcanics of mainly rhyolitic, felsitic, and dacitic rocks and linked to the hydrothermal alteration zones (Fig. 3C) and related mineralized quartz veins (Fig. 3D).

The abundance of sub-aerial silicic lavas in the Abu Marawat metavolcanics suggests that they were erupted from a mature arc (*e.g.* Habib, 1987; Aly *et al.*, 1991; and Fowler *et al.*, 2006). The massive and foliated mafic metavolcanics and related tuffaceous units are represented by flows and tuffs of meta-andesite and less common metabasaltic flows and agglomerates (Fig. 2). Felsic metavolcanics range in composition from dacite to rhyolite and in texture from banded schistose to tuffaceous. Generally, the metavolcanic rocks exposed at the Abu Marawat area were subjected to multiple deformations and were dislocated along sub-parallel NW-SE-oriented left-lateral strike-slip faults and NE-SW-oriented right lateral strike-slip faults. The displacement is very clear and may reach 1km in some places (Fig. 2).

Resistant BIF to the east of Abu Marawat covers an area of about 700m x 300m located mainly on the summit of G. Abu Marawat. Bands of iron up to 3m thick are interlayered with slates and phyllites. Few BIF outcrops are intercalated with the metavolcanics as in the mine area to the north of Wadi Abu Marawat. The iron formation-bearing succession of Abu Marawat area attains a thickness of 76m. The BIF is mainly present in the middle and upper part of the iron formation succession. It is similar to most worlds BIF where the bands are strongly persistent, and show remarkable isoclinal, tight and open fold styles. BIF is present in three main intervals terminating three large depositional cycles (Fig. 4). Each of these large cycles begins with a relatively thick tuffaceous mudstone of dark green color and fine-grained texture at its lower part

(Fig. 4A), which becomes yellowish green colored and coarse-grained texture toward the middle part of these cycles (Fig. 4B). The mudstones terminated upward by the BIF-bearing intervals (Fig. 4C). The lower parts of these cycles show evidence supporting the deposition during shallow marine environment. This is confirmed by the appearance of yellowish green and red tuffaceous mudstones which indicate the deposition in a slightly oxidizing environment (*e.g.* Mesaed, 2005). The upper part of the three cycles was deposited in more oxidized environment where it contains red tuffaceous mudstones intercalated with red hematitic iron formation bands as the common setting of Algoma-type (Fig. 4D). Generally, Abu Marawat BIF is located adjacent to Abu Marawat volcanics where iron and silica were derived from hydrothermal sources associated with volcanic centres at the time of formation.

The arc-related plutonic rocks include coarse- and medium-grained gabbro and diorite. Intrusions of syn-tectonic tonalite and quartz-diorite are emplaced in the metavolcanic rocks at the northern and southeastern parts of the mapped area (Fig. 2).

The Hammamat sediments are represented by green to purple pelites, with lesser intervals of arenite ranging from 20cm to over 10m. They strike north and dip toward the east and are located to the west of the mapped area (Fig. 2).

Analysis of Mesoscopic Structures

The recognized mesoscopic structures were used in this study to reveal the large-scale structures and to reconstruct the local tectonic history of Abu Marawat area. Based on the detailed field mapping and analysis of the structural data, the study area is affected by at least four successive phases of deformation named D₁, D₂, D₃ and D₄. Compression regime was associated with the first two deformational phases and is characterized by folding, thrusting, early steep dip-slip normal faults, and brittle shear zone. Brittle strains were associated with D₃ and D₄ and are characterized by strike-slip and dip-slip normal faults, respectively. The following is a detailed description of each structural element and its relation to the deformational history. They include shear zones, small-scale fold hinges, foliations, quartz veins and faults. Geometrical analysis was used to portray and reconstruct the three-dimensional shape of BIF and the gold bearing quartz veins.

Fig. 2. Geologic map of Abu Marawat area showing alteration zone and the major structural elements.

Fig. 3. (A) North eastern side of Abu Marawat area showing BIF, Serpentinite “Sr” and listwanite “L” in contact with metavolcanics “MV”, (B) SE-directed imbricate thrust stacks along talc carbonate layers “TC”, metavolcanic “MV” (note thrust-propagation folds in BIF), (C) Highly altered and sheared felsic metavolcanics, (D) Swarm of mineralized quartz veins developed along predefined shear fractures in altered rhyolite.

Foliations

Foliation in the area includes slaty cleavage, phyllitic structures and schistosity in metasedimentary rocks, and fracture cleavage in metavolcanics and BIF. Early foliation “ S_1 ” runs parallel to the bedding (S_0). Foliations are formed during the early ductile phases of deformation associated with folding. Some axial plane foliations are parallel to the tight fold axes and crossing the hinges. Some foliations are crenulated during the overprinting of F_3 folding generation. The attitudes of 127 foliation planes are measured throughout the entire area and plotted on stereograms (Fig. 5 A). Inspection of the contour diagram of poles to S_1 -surfaces (Fig. 5A), the rose diagram (Fig. 5B), and the pole diagram (Fig. 5C) indicate that the orientation data show some extent of dispersion as an indication of heterogeneous structures occupying the area under

consideration and the presence of polyphase folding generations. However, two main clusters can be recognized; the first strikes NE and dips to NW at a moderate angle. The second cluster strikes NW and dips to NE at a moderate to steep angle. The sequence of events and the location of major structures are mainly field-based interpretation.

Fig. 4. Field photographs showing large-scale stratigraphic cycles of BIF (A) The lower tuffaceous mudstone "TM" and sheeted IF bands "BIF" of the first cycle, (B) Bedded yellowish green hematitic-magnetitic IF bands "BIF" and red tuffaceous mudstone in the uppermost part of the first cycle, (C) Magnetitic and hematitic- IF bands "BIF" and yellowish green tuffaceous mudstone in the middle and upper part of the second cycle, (D) Red tuffaceous mudstone and red thick hematitic BIF zone of the uppermost part of the depositional cycles.

Mesosopic Folds

Mesosopic folds encountered in the area are recognized everywhere and show variable style and different orientations. They are best recognized in BIF and metasedimentary rocks. Generally, they are used to locate the large scale folds based on their similarities in both style and orientation (*e.g.* El-Shafei and Kusky, 2003).

Fig. 5. Lower hemisphere equal-area projections and rose diagram of structural elements (A) Contour diagram of poles to 127 foliation planes (B) Rose diagram shows the strike trends of foliations (C) Pole diagram showing cluster distribution of poles to 127 planes (D) Point diagram of 25 small-fold hinges (F_1 plunges 31° due $S62^\circ W$, F_2 plunges 86° due S and F_3 plunges 18° towards $S26^\circ E$).

Fold types at Abu Marawat area range from isoclinal to open fold styles. They show steeply plunging tight folds (Fig. 6A), E-plunging close folds (Fig. 6B), and SE-moderately plunging open folds (Fig. 6C). Three folding generations (F_1 , F_2 and F_3) are defined based on the recognized interference patterns. BIF shows the effect of superimposed folds and their sequence clearly at the summit of G. Abu Marawat where early isoclinal NE trend F_1 folds are refolded by F_2 tight folds (Fig. 6D).

F_1 folds are associated with boudin lines (Fig. 7A) parallel to the foliation. Whereas, crenulation foliation is associated with F_3 open folds (Fig. 7B). S-plunging F_2 folds are refolded by F_3 close folds (Fig. 7 C & D).

Fig. 6. (A) Tight F_1 minor fold in BIF (B) Close F_2 fold of nearly vertical axis (C) SE plunging F_3 open fold in interlayering of metasediment and metavolcanic units, (D) F_1 isoclinal fold refolded by F_2 tight fold with vertical axial plane and steeply plunging due SE.

The attitudes of 30 small fold hinges are measured and projected on an equal-area diagram (Fig. 5D) Inspection of the diagram shows near alignment along a great-circle trending NE-SW and steeply dipping towards NW. The alignment of F_1 and F_2 hinges could be interpreted as a consequence of rotation during refolding by F_3 folds. F_1 and F_2 show different orientation throughout the entire area and the pole to the great circle including them defines the orientation of F_3 open fold axis (Fig. 5D).

The measured F_3 axes are coaxial with the statistically defined axis (Fig. 5D). It plunges 15° to $S29^\circ E$.

Shear Zones

Shear zones are one of the remarkable tectonic fabrics recognized in both altered and non-altered metavolcanics of Abu Marawat area. They include ductile, brittle-ductile, and brittle shear zones. MQV in metavolcanics and Porphyroclasts recognized in the serpentinite rocks show early ductile shearing. Right-lateral sense of shear shown by S-C fabric relation is an indication of brittle-ductile shearing (Fig. 7E). Brittle shear zones are the most dominant type recognized in the area (Fig. 3D). They are developed either parallel to the early formed metamorphic foliations or are intersecting them. Few conjugate shear planes are also recognized. They were later filled by swarms of mineralized quartz veins (Fig. 3D) of post D_2 and pre- D_3 .

The attitudes of 75 shear planes are measured throughout the entire area. They are projected on a stereogram as poles, great circles and as density distributions (contours) (Fig. 8A). Inspection of the stereoplot (Fig. 8A) and the rose diagram (Fig. 8B) shows that the main shear trends are striking $N20^\circ W$ - $S20^\circ E$. They are moderately to steeply dipping towards ENE and WSW. They were formed during late D_2 as a result of a NNE-SSW-oriented compression regime.

Quartz Veins

MQV (Fig. 3D) at Abu Marawat area are associated with kaolinized and silicified alteration zones (orange color Fig. 9A). They are most abundant near the northern part (Fig. 9B), less abundant at the middle part and are rare at the southern part of the mapped area where metasediments predominate. The pronounced lithologic control is indicated by the developed of MQV primarily in a rheologically competent mafic and acidic volcanic rock.

MQV typically occur in subparallel swarms crosscut the host rock and run mainly parallel to the metamorphic fabric. Most veins are less than 20 cm wide and 1 m long but some larger veins occur, with ca. 2 m width and 10's of metres in length. At the northern part of the mapped area, they show thicknesses that increase downwards. Few randomly orientated veins and stocks are recorded. Some MQV are developed along conjugate shear fractures.

Fig. 7. (A) Silica rich layers in BIF showing boudin lines parallel to F_1 folds developed in the extension direction, (B) Crenulation foliation ($S30^{\circ}E/47^{\circ}NW$) in metasediment associated with F_3 open fold, (C) Large-scale tight F_2 folds refolded by F_3 closed folds, (D) Traced sketch showing the feature relations in C, (E) S-C fabric indicates right-lateral sense of shear.

Fig. 8. Lower hemisphere equal-area projection and rose diagram, (A) Pole diagram and its contour equivalent of 75 shear planes, (B) Rose diagram shows the strike trends of the measured shear planes, (C) Pole diagram and its contour equivalent of poles to the mineralized quartz veins, (D) Rose diagram shows the strike trends of 63 mineralized quartz veins.

Fig. 9. (A) Landsat ETM⁺ band image (bands 5/7, 3/1, 3/5 in RGB) showing the alteration zones in orange color; (B) Traced map of A showing altered volcanic rocks that host the mineralized quartz veins (MQV).

The attitude of 63 quartz veins are measured and geometrically analyzed. They are plotted as great circles; poles to planes and as contour diagram (Fig. 8C) and are plotted on a rose diagram (Fig. 8D). Investigation of the diagrams shows that they are striking mainly N-S and NNW-SSE with moderately to steeply dipping towards ENE and WSW. It could be concluded that the MQV are running along predefined shear fractures (Fig. 8B&D). The comparison with the shear zones orientations (Fig. 8B) indicates that MQV are developed along predefined shear fractures. They are formed post-D₂ and pre-D₃.

Barren quartz veins (BQV) are developed along tension fractures (Fig. 10A, B). They crosscut the MQV and their metavolcanic host rocks. They are trending mainly N30°E and steeply dipping 80°SE. They represent the final stages of quartz veins in the area and are associated with tension fractures resulted from simple shear stress accompanied with D₃ phase. Opening of tensional fractures were parallel to σ_1 and normal to σ_3 (Fig. 10B).

Preliminary field data are collected during this study at the metavolcanic hosting quartz veins at Hamama area located farther west of Abu Marawat (Fig. 1). It indicates similar vein systems, alteration, and structural setting. Mineralization in the area is associated with white quartz veins rich in specular hematite and is developed along shear zone striking N15°W-S15°E and steeply dipping towards ENE and WSW.

Faulting

Faults are the most important structural elements that play a significant role in controlling the location and orientations of the mineralized zones. Two types of faults are recorded throughout the mapped area; the dip-slip (normal and reverse) and strike-slip faults (Fig. 2). Low angle reverse faults are represented by early overthrust and the development of thrust-propagation folds (Fig. 11A, B) associated with D₁ phase. The transport direction was coming from NW directed to SE and resulted in the formation of imbricate thrust stacks (Fig. 11A, B). Mylonitized rocks and listwanite distribution are used to follow and trace the thrust stacks in the area (Fig. 2, 3B).

Fig. 10. (A) An E-W-trending barren quartz vein in meta-andsite developed along tension gashes associated with strike-slip faults, (B) Mineralized quartz veins (MQV), barren quartz veins (BQV), and shear fractures relationship with the maximum principal stress axis.

The measured attitudes of the fault planes and their cross-cutting relationship and their relation to mineralized quartz veins indicate the presence of two main fault generations. The early NNE trend with near vertical planes is the only mineralized fault trend and formed contemporaneously with brittle shearing of late-D₂. They acted as a channel for movements of hydrothermal solution expressed by alteration and gossan zones. The second group of normal faults strike mainly to NW-SE and NE-SW with moderate dipping toward NE and SE. The local extensional setting of the area facilitated fluid migration from depth. Fluid flow is enhanced adjacent to faults by local extension ascribed to the relative rotation of rigid blocks of host rocks (Fig. 10B). Hence, permeability for mineralization in the northern section is related

primarily to variable physical disruption of the rocks on a crustal scale at fault intersection zones.

The strike-slip faults trend towards NW-SE and NE-SW (Fig. 2). They are dextral (Fig. 11D) and sinistral faults representing conjugate-shear planes that have been formed as a result of simple shear stress oriented nearly E-W during D₃ phase. Tensional gashes filled with barren quartz veins accompanied this regime.

Fig. 11. (A) Minor imbricate thrust stack associated with F₁-isoclinal folds, (B) Traced sketch showing the feature relations in A (ramp, thrust plane, direction of slip, kink folds, early F₁ folds and back and fore thrusts), (C) Sinistral strike-slip fault trending NW-SE and dislocating aplitic dike in metavolcanics, (D) Dextral strike-slip fault in metasediments.

Gossans and Gold Mineralization

Mesothermal vein type gold deposits are structurally controlled vein systems found in exhumed metamorphic belts, principally in greenschist facies rocks. Economic deposits typically occur close to major crustal structures such as faults or shear zones (Vearncombe *et al.*,

1989 and Craw and Campbell, 2004). In the study area similar structural elements include shear zones and related alterations are recognized in the metavolcanosedimentary sequence formed under greenschist facies.

Mineralizations at Abu Marawat area are intensely recorded in a wide variety of extensional sites that are dislocated laterally by regional brittle structures. Rock alteration and gossan zones are enhanced by hydrothermal activity. They are clearly recognized at the intersections of dip-slip normal faults (N-S trend) and shear zones. Altered metavolcanics hosting quartz veins are exposed at the northern and the central parts (Fig. 2&9A), while iron gossans occur at the southern part of the mapped area (Fig. 11D).

Gossan as defined by Jambor and Blowes (1994) is the name given to a large mass of residual Fe oxyhydroxide material formed by the oxidation of Fe-bearing sulfide ore deposits. Gossans are oxidized caps that form due to sulfide oxidation, dissolution, and precipitation of secondary minerals. They crop out at the southern part of Wadi Abu Marawat (Fig. 9B) and to the NE of Wadi Semna. Intersections of dip-slip normal faults (NW-SE and N-S trends) were the favorable sites for gossans to develop.

Gold occurrences are concentrated mainly along sheared and fracture zones. Vein-type gold mineralization occurs along alteration zones in metavolcanic and metasedimentary rocks. The mineralization is confined to N-S to NNW shear and fracture zones ranging from 5-500cm in width and 1-5 km in length.

The primary ore minerals or phases at Abu Marawat (as reported by MINEX, David, 1988) include a polymetallic sulphide deposit with multi-phase mesothermal vein systems and three phases of mineralization: (1) early high-temperature: pyrite, chalcopyrite, sphalerite, stannite, and galena; (2) low-temperature, low-sulfidation (retrograde metamorphism) pyrrhotite; and (3) low-temperature, high-sulfidation pyrite and tellurides. MINEX has drilled from the surface to 60 m depth in rhyolite and andesite. Grades average 5.3 g/t Au, 63.3 g/t Ag, 0.54% Cu and 1.8% Zn. Gold forms fine inclusions dispersed in goethite, limonite, and malachite. Listwanite derived from the alteration of mafic and ultramafic rocks contains an average gold content of 2.7.g/t. Anomalous gold values up to 1.75 g/t gold were recorded in BIF.

Structural Control on Mineralization

Three main settings are recognized for gold mineralization in Abu Marawat area: (1) Shear-zone hosting quartz veins. It is characterized by the presence of steeply-dipping NNW-SSE striking quartz veins. The host rocks are mainly altered and sheared meta- rhyolites, felsites, and andesites. (2) Small bodies of hematitic gossans. They are recognized at the southern part of the area and located in weakly to non-altered zones controlled by normal faults intersections and accompanied with few mineralized quartz veins. They may indicate the presence of possible massive sulphide beneath them. (3) 'Listwanite-type' carbonate-altered thrust fault controlled mineralization. Listwanite (carbonated-serpentinite) crops out forming an N-S trending, 800m long serpentine-listwanite belt that has an average thickness of 30m. The zone is gold - bearing and is associated with thrust movement. Similar small-outcrops of listwanite are also distributed throughout the mapped area controlled by a basal thrust fault.

Conclusions

Gold mineralization at Abu Marawat area in the central Eastern Desert of Egypt is localized mainly in a belt of meta-volcanosedimentary sequence. The near-surface mineralized quartz veins may grade into replacement bodies at depth. The presence of BIF at Abu Marawat is a favorable indicator for gold mineralization related to massive sulphide or iron formation. Gold mineralization occurs throughout the history of the area and developed at many structural levels from the brittle-ductile transition to near surface, and is a normal consequence of collisional tectonics involving mainly greenschist facies rocks.

Structure is arguably one of the principal controls of mineralization. It leads to the formation of high fracture shear zones which provide pathways of enhanced permeability and fluid-flow during syn- and post-metamorphism. This study highlighted the importance of litho-facies, structural evolution, and hydrothermal alteration in the localization of fluid flow at the time of mineralization.

The present structural architecture of Abu Marawat area is the consequence of at least four successive phases of deformation. The exposed metavolcanics and metasediments have been deformed

extensively by ductile flow. The resulting structures include thrust-propagation folds. These rocks are invariably thrust and transported towards SE direction. Multiple generations of folding produced a variety of folds interference pattern. Structural sequence that emerged from the geometric analysis includes F_1 -isoclinal folds associated with thrusting refolded by upright F_2 -isoclinal folds. These F_1 and F_2 folds are of flexural-slip nature resulted from pure shear regime that has acted in NW-SE direction. The F_3 -folds represent the final folding generation overprinting the early-formed folds and plunge 15° towards $S29^\circ E$.

Thrust stacks trending NE-SW are aligned with folds. Both the vergence of folding and the propagation of thrust stacks were towards SE. This deformation was the product of NW-SE compression and is associated with greenschist facies regional metamorphism. These thrust faults control the distribution of serpentinite and listwanite bearing of gold. Folding and refolding in addition to thrust movement play a significant role in shortening and thickening of the iron formation bands located at the summit of Gebel Abu Marawat and provide an easy access for an open pit mining from its eastern side. Few iron formation outcrops of maximum three meters width are recognized intercalated with metavolcanics and other metasedimentary units.

D_2 at outcrops record a switch to NE-SW compression and the development of SE plunging F_3 folds. They overprint the early formed fabrics; F_1 folds, thrust related listwanite and F_2 folds. F_3 are represented by folds oriented NW-SE. Second-order asymmetric folds affecting the limbs of the main structures indicate a slip mechanism of folding in a multilayered and mechanically heterogeneous succession during D_2 . The axial plane foliations acted as weak planes along which later shear zones and strike-slip faults took place. Brittle shear zones striking mainly NW-SE are the channels along which mineralized quartz veins were developed.

During D_3 the exhumations of the metamorphic belt led to the formation of conjugate shear planes which may be associated with the Najd Fault corridor. Strike-slip faults are distinguished into NE-SW (dextral) and NW-SE (sinistral). E-W trending tension gashes were developed as a result of simple shear regime which exerted E-W compressive stress. Barren quartz veins were developed later along these tension gashes.

A switch to crustal extension during D₄ and subsequent rotations of the principle stress axes led to granite emplacement and contemporaneous N-S faulting under east–west extension.

Recommendations

1- Within the volcanic-metasedimentary sequence, the well-known Au-bearing quartz vein(s) are promising prospects. In addition, there is a possibility of Listwanite-type Au mineralization to occur within the volcanic sequence, particularly in the eastern portion of the mapped area and along the thrust planes.

2- Altered rocks obliterate most of structural parameters used to define the sense of movements and the type of structures controlling mineralization within the alteration zones. It is recommended, based on the detailed survey to explore the area around the alteration zone. Non-altered rocks will give a clear picture about the situation of these rocks before alteration took place.

3- Thrust related listwanite bodies are considered as suitable sites for gold exploration. Whereas normal and strike-slip faults played a significant role in redistributing quartz veins and their hosting rocks.

4- The occurrence of gold in quartz veins with other sulphides encourages the use of geophysical methods like induced polarization to record differences in conductivity and resistivity at depth and to relate these readings to gold potentials in the mineralized zones.

5- Iron gossans exposed at minor localities in sheared/non-altered metavolcanics at the southern part of Abu Marawat area are recommended for carrying out chemical analyses necessary for mineral exploration.

6- Drilling for new massive sulphide deposits and /or porphyry ores should be targeted where hematitic gossans are well-developed.

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التحكم التركيبي في متكون الحديد الشرائطي وتمعدنات الذهب بمنطقة أبومروات بوسط الصحراء الشرقية، مصر

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المستخلص. منطقة أبومروات تضم تتابعاً من الصخور المتحولة منخفضة الدرجة عند سحنة الشست الأخضر، وينكشف الأنديزيت، الداسيت، الريوليت والفلسيت كصخور بركانية الأصل إلى جانب الإردواز - الفليت والشست ذات الأصل الرسوبي والمصاحب لهما متكون الحديد الشرائطي (BIF). يوجد أيضاً متداخلات متعاقبة من الصخور النارية الجوفية مثل الجرانيت والديوريت. شواهد حفر قديمة وأخرى حديثة في محاولة لاستخراج الذهب والمعادن المصاحبة له بعدد من عروق الكوارتز المنكشفة على السطح أدى إلى لفت الانتباه وعمل عدد كبير من البحوث المتعلقة بكميائية وجيولوجية تلك العروق والصخور الحاوية لها. تهدف الدراسة الحالية إلى معرفة التاريخ التركيبي (البنائي) لصخور المنطقة وما تحويه من تمعدنات، ويشمل ذلك دور العناصر البنائية وما تلعبه من دور حيوي سواء إيجابي أو سلبي في توزيع تلك الرواسب، حيث تعمل التراكيب الجيولوجية المتعاقبة على توجيه - تركيز - إخفاء أو إزاحة للصخور ورواسبها المعدنية.

أسفرت نتائج المسح التفصيلي لمنطقة الدراسة من مشاهدات حقلية وقياسات للعناصر البنائية على النتائج والتوصيات التالية:-

١- صخور المنطقة الحاوية لعروق الكوارتز الحاملة للتمعدنات تمثل نطاقات قص هشة ونطاقات تغير حرمانية.

٢- توجد عروق الكوارتز بكثرة في الصخور البركانية كحشود شبه متوازية على شقوق القص. كما توجد بقلة في الصخور الرسوبية الأصل، وتتخذ اتجاهات وأنماط مختلفة، فمنها الكتلي، والعروق السمكية، والعروق الدقيقة، كدلالة على كونها نمت على شقوق سابقة التكوين وفي مراحل متعاقبة.

٣- عروق الكوارتز موجودة في الصخور البركانية سواء القاعدية أو الحامضية المتغيرة منها أو غير المتغيرة.

٤- تنتشر عروق الكوارتز شمال وادي أبومروات، ونقل كلما اتجهنا جنوبا متخذة من اتجاه شمال شمال غرب مضربا لها، وبدرجة ميل متوسط إلى شديد جهة الشمال الشرقي.

٥- تظهر صخور الجوسان بالقرب من وادي سمنا جنوب وادي أبومروات.

٦- نطاق الجوسان محصور بين منجم أبومروات ومنجم سمنا، ولذلك لم تحظ بدراسات سابقة، وهي مناطق واعدة وهامة للرواسب الكبريتيدية الكتلية، واحتمالية وجودها في العمق تحت تلك المنكشفات المحدودة الوجود وتحتاج إلى دراسات جيوكيميائية وجيوفيزيائية.

٧- صخور اللستفانيت listwanite موجودة ليس فقط في منطقة المنجم، ولكنها منتشرة داخل الحزام المتحول على طول مستويات صدوع الدسر، وتعتبر هدفاً إضافياً لمعادن الذهب.

٨- لعب الطي دورا حيويا في تقصير وتركيز طبقات الحديد، وأفضل مكان لعمل منجم من النوع المفتوح Open Pit هو من الجهة

الشرقية، حيث يستغل الحديد ومعادن الذهب المصاحبة له. تم أيضا خلال تلك الدراسة معرفة الوضع الهندسي لطبقات الحديد فى الأبعاد الثلاثية.

٩- تم استنتاج أربعة أطوار من التشوه المتعاقب من خلال فحص وتحليل البيانات التركيبية. الطور الأول والثاني من النوع التضاعطي compressional، والذي أدى إلى تحول إقليمي لصخور المنطقة والمصاحب له تكون ثلاثة أجيال من الطي المتراكب، والصدوع الدسرية . أما الطور الثالث والرابع أدى إلى تشوهات هشة وظهور الصدوع المضربية بإزاحتها الأفقية، والصدوع العادية على التوالي.

١٠- تم ربط أطوار التشوه المتعاقبة بنوعية التمعينات المصاحبة لها، وكذلك اتجاه الإجهاد المصاحب لكل طور والسبب وراء تعدد نمط واتجاه التشوه.