Original Article

Microfabrics and microchemistry of sulfide ores from the 640 FW-E level at the Al Amar gold mine, Saudi Arabia

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\begin{abstract}
In a VMS ore at Al Amar gold mine (level 640 FW-E), sulfide minerals are paragenetically ordered as follows: pyrite(I)–sphalerite–chalcopyrite–galena–pyrite(II), deformations vary from brittle to ductile deformation fabrics. Microscopically, the massive sulfides have pyrite porphyroblasts (up to ~80%) that show evidence of creep dislocation as a result of low-temperature plastic deformation rather than brittle failure, whereas high-temperature annealing is completely lacking. Softest minerals such as chalcopyrite fill into fractures in pyrite as narrow slivers. Needle-shaped or lamellar morphology of chalcopyrite, together with the chemical composition of Fe-poor sphalerite (with maximum 0.99 wt% Fe) suggest a combined replacement–coprecipitation mechanism of chalcopyrite disease formation rather than an exsolution texture. Greenschist facies metamorphism produces an ore with distinct chalcopyrite disease into a stratified ore with microbands of chalcopyrite and sphalerite. Ore microfabrics and uncommon occurrence of epithermal stringers suggest noticeable effect of the Najd tectonics in the studied level. The EMPA analyses indicate that all sulfide minerals in the VMS ore are auriferous and the Au contents are considerable (up to 0.94, 1.31, 0.16 and 1.20 wt%; in sphalerite, chalcopyrite, galena and pyrite, respectively). Gold in pyrite is “invisible” whereas it occurs as submicroscopic inclusions in sphalerite, chalcopyrite and galena. The VMS ore of Al Amar deep horizons are characterized by the occurrence of “invisible gold”, Ag-free galena, Fe- and Ni-poor sphalerite, negligible hydrothermal alteration, plastic deformation of pyrite and non-exsolution origin of the chalcopyrite disease intergrowth which are together strong indicators of low-temperature (250–300 °C).

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\end{abstract}

1. Introduction

Exploration and exploitation of gold in Saudi Arabia attracted many researchers and mining companies in order to fit models of ore genesis and processing during the last four decades [1,2]. In the Neoproterozoic Arabian Shield of Saudi Arabia, some major gold mines are in production such as Mahd Adh Dhahab, Al Amar, Al Hajar, Bulghah and Sukhaybarat (Fig. 1). In addition to these major productive prospects or goldfields, some mining companies (e.g. Ma’aden, Arabian Gold and Citadel) currently conduct feasibility studies for the ore exploitation in some other prospects such as Ar Rjum, Umm Matierah, Bi’r Tawilah, Al Amar south and Shayban [1].

Primary gold mineralization in the Arabian shield can be classified into three main types based on the tectonic settings and host rocks [2]. The first type is associated with volcano-sedimentary sequences (hosted by the Siham
and Hulayfah Groups), which were deposited in juvenile oceanic environments and were later accreted to form crustal blocks before final amalgamation. The class includes gold-rich volcanicogenic massive Cu-Zn sulfide deposits at Jabal Sayid and Wadi Bidah shear zone [35], and the epithermal base and precious metal deposits in both Mahd Adh Dhabah and Al Amar. Gold in some deposits of this class may have been remobilized during the Najd Fault System to form epithermal mineralizations superimposed on the massive sulfide deposits [3,4]. Some of these deposits were subjected to supergene enrichment processes due to chemical weathering processes. Mercier-Langevin et al. [5] reviewed 513 VMS deposits in the world and assigned high-grade auriferous ones as higher as 3.46 g/t and added that some of the Nugrah VMS deposits in Saudi Arabia assay 3.80 g/t gold. The second class of gold deposits is spatially associated with carbonatized ophiolitic serpentinites rocks (listvenites), which were formed along suture zones during the amalgamation of the different terranes, e.g. at Bi‘r Tawilah, Bi‘r Umq and Jabal Al Wask [6,7]. The third class of gold deposits is particularly abundant in the western parts of the so-called “Aff terrane” to the east of the Nabihah suture zone, where syn-to late-tectonic diorite to granite plutons intruded the arc metamorphosed volcanicslastics (Siham and Hulayfah Groups) and post-amalgamation slightly metamorphosed rocks of the Murdama and Bani Ghayy Groups, e.g. Sukhaybarat, Zalm, Bulghah, Bi‘r Tawilah, Ad Duwayhi and Jabal Ghadarah deposits [8,9]. These deposits are mesothermal and are characterized by low sulfide content (typically arsenopyrite, pyrite and/or pyrrhotite) that deposit from CO2-rich ore fluids as indicated by the detailed mineralogical and fluid inclusion studies in the Zalm mine area. In addition to secondary oxidation zones with common auriferous gossans, placers in some goldfields represent promising targets for low-cost gold mining, e.g. Mahd Adh Dhabah, Jabal Mokhyat and Hamdah or Hajr [10,11] as another type of secondary gold mineralization in Saudi Arabia.

The Al Amar goldfield (23°47’ and 45°03’ E) is one of the major prospects for gold in the Precambrian shield rocks of Saudi Arabia (Fig. 1). According to [12], some important mineralized sites are located in the Al Amar Group with close confinement to the Al-Amar-Idsas fault (Fig. 2). They include sites for base metals (Al Amar, Khnaiguway and Marjan) and precious metals (Al Amar, Umm Ash Shalah, Al Taybi and Umm Ad Dabah). Early exploration programs at Al Amar were in the scope of zinc prospection from 1950s until 1980s, and then a special attention was given to the presence of precious metals in the prospect. Due to the common presence of ancient workings, the Directorate General of Mineral Resources of Saudi Arabia (DGMR) started to examine and sample the old pits. The DGMR continued investigation for zinc and executed an underground exploration program, with a total of 909 m intersections from 1974 to 1976. Extensive exploration by the Riofines Mining Company indicated resources of 1.077 Mt grading 33.1 g/t Au and 7.79% Zn in the North Vein Zone (Fig. 3). This was followed by intensive drilling of 49 boreholes with a total depth of 13,338 m by Petromin Middle East in the same vein zone [9]. Recent exploration by Arabian Gold Corporation [13] some 35 km to the south of Al Amar gold mine indicates promising extension of economic VMS deposits with 1.55 Mt@12.3 g/t Au, 21.1 g/t Ag, 6.16% Zn and 0.92% Cu.

The present work presents the first detailed ore fabrics, sulfide mineral chemistry and possible genesis of a newly explored deep horizon in the Al Amar gold mine at the 640 footwall level below the eastern part of the mine, particularly beneath the Northern Vein Zone. This includes detailed ore microscopic investigation for accurate specification of ore mineral paragenesis, their paragenetic sequence and style of deformation on the microscopic scale. Also, the study aims investigate if the shear effect of the Najd fault system extends deep enough to deform the VMS ores in deep levels, or its effect is localized to shallower levels.

2. Regional geology

The late Proterozoic Arabian Shield is dominated by rocks and ores that are contemporaneous to the Pan-African orogeny, and the shield consists mostly of juvenile crust that originated by transpressive suturing between East and West Gondwana [14,15] that culminated ~550 Ma. It was formed through a prolonged history.
of accretion of mainly intraoceanic island arcs along sutures now marked by ophiolites [16–18]. These accretions episodically occurred between 900 and 550 Ma ago, as the Mozambique Ocean was closed. Accretion may also have included an oceanic plateau formed by the head of an upwelling mantle plume. The Arabian Shield in Saudi Arabia is only slightly metamorphosed (except for some areas of gneissic rocks) and it constitutes one of the best preserved and well exposed Neoproterozoic assemblages resulting from the accretion of volcanic arcs. It is overlain to the east, north, and south by a thick succession of Phanerozoic sedimentary rocks, and is bounded to the west by the Red Sea that now separates the individual Arabian and Nubian Shields in western Arabian Peninsula and NE Africa, respectively. According to [19], the Arabian Shield rocks are exposed at present time as a result of Late Mesozoic uplift in the west-central part of Saudi Arabia resulting in a structural high referred to as the Ha’il arch, and Cenozoic uplift along the western margin of Saudi Arabia, in association with Red Sea spreading. According to the tectonic terrane concept, the Wadi Ar Rayn terrane, that includes the Al Amar goldfield, is of probable continental origin in contrast to other terranes in the Arabian Shield (AS) that pertain intraoceanic island arc terranes, for example Midyan, Hijaz and Asir [20,21]. Detailed survey of the volcanosedimentary basins in the Arabo-Nubian Shield reveals that orogeny was closely linked with subsidence and deposition, and this represents an excellent example of crustal growth at the end of the Precambrian and a prime target for calibrating Neoproterozoic Earth history [22].

Al Amar village and its mineralized environs is located at the eastern extremity of the AS crystalline rocks near the contact with the Phanerozoic sedimentary cover (Fig. 2), some 200 km to the southwest of Ar Riyadh (Riyadh) city along the highway that connects the capital with the harbor city of Jeddah on the Red Sea, at the so-called “Wadi Ar Rayn quadrangle”. This quadrangle contains some of the oldest gneisses in the Arabian shield, in addition to ophiolitic rocks, a thick pile of arc metavolcanics in association with volcanogenic carbonates, chert and jasper, and a younger association of intrusive rocks that are represented by granitoids, granites and dyke swarms of different ages [23].

About 1/4 of the Wadi Ar Rayn quadrangle area (latitudes 23°00′–24°00′ and longitudes 45°00′–45°30′) is occupied by shield rocks whereas the 3/4 is occupied by gently dipping Phanerozoic sandstone and limestone. The late Proterozoic AS in the quadrangle is distinguished into

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Fig. 2. Geological map of the gold belt that include Al Amar gold mine along Al Amar-Idsas Fault in the Wadi Ar Rayn quadrangle. From [28].
two main lithostratigraphic units that are separated by the Al Amar-Idsas mega fault (Fig. 2). To the east of the fault, carbonatized serpentinite, metamorphosed mafic to intermediate volcanic rock with pillow structures, chert and small intrusion of plagiogranite, in addition to arc metavolcanics outcrop and fill a large synclinorium. Further to the north (e.g. Halaban and Ad Dawadmi quadrangles) outside the area shown in Fig. 2, this ophiolitic and arc assemblage are unconformably over lain by a thick succession of flyschoid sediments, mainly greywacke and shales as the major components of the so called “Abt Formation” [24,25] at the western side of the Al Amar-Idsas Fault. From the structural point of view, both the ophiolitic assemblage and the Abt Formation were folded and metamorphosed in the greenschist facies during at least two major phases of deformation including the Idsas phase that produced the Al Amar-Idsas Fault as a mega thrust zone [26]. The northern segment of the Al Amar-Idsas Fault is a single high-angle thrust outlined by a thin band of serpentinite and listvenite whereas the southern segment is divided into sub-segments in which the ophiolitic rocks, a part of the Abt Formation and younger units such as the Al Amar and Hamir Groups (arc metavolcanics) were subjected by small scale and high angle thrust fault system [25]. According to the latter workers, both the ophiolitic assemblage and the arc metavolcanics were intruded by ∼630 Ma.
syn-orogenic Pan-African calc–alkaline granitoids (tonalite and trondhjemite), followed by post-orogenic calc–alkaline and alkaline microgabbro and microgranite that have been affected partially by the epi-orogenic movement of the major NW Najd fault system that dominates in the AS with extension further to the west in the Nubian Shield of Egypt and the Sudan.

3. Geology of Al Amar goldfield area

In the Wadi Ar Rayn terrane, the layered successions that unconformably overlie the ophiolitic rocks are called “the Urd Group” (Ar Ridayniah and Abt formations) which is equivalent to the Baish and Bahah Groups in the southern parts of the AS [40]. The Abt Formation covers a vast area of the map (Fig. 2) and consists of a thick alternating folded succession of conglomerate, greywacke, siltstone, shale and subordinate volcanic flows. The Abt formation shows different metamorphic imprints in terms of greenschist facies regional metamorphism (quartz–chlorite–sericite schist) and superimposed contact metamorphism that produced garnet–biotite hornfelsic schist. Age of the Abt Formation can be much old as 800 Ma as it is intruded by 724 Ma trondhjemite [27]. To the east of the Al Amar Idas Fault, the area is occupied by a thick succession of volcanosedimentary rocks that belong to the Al Amar Group (Fig. 2). Calvez et al. [27] determined 667 Ma age of the Al Amar Group. Lofts [4] summarized that Al Amar Group is intruded by syn-orogenic 700–600 Ma gabbro, quartz-diorite, granodiorite and trondhjemithe, as well as by post-orogenic 600–550 Ma granite. Al Amar Group (equivalent to Halaban group in northern terranes) itself is sub-divided into lower massive metandesite and upper silicic volcanic flows, pyroclastic and epilastic rocks [25].

Based on their lithological and geochemical characteristics, Pouit et al. [28] distinguished the Al Amar Group into 4 volcanic units as follows from oldest to youngest (Fig. 3). Thickness of each unit is ~100 m in average with the exception of the 1st unit that is 300 m [28] and up to 600–700 m [29].

**Volcanic Unit 1**: Common intermediate and subordinate mafic pyroclastics that are intercalated with ash-falls, and an upper effusive andesitic to rhyolitic lava flow.

**Volcanic Unit 2**: Felsic pyroclastics are dominant, with subordinate intercalations of jasper and chert bands. These bands represent Fe- and silica-rich submarine volcanic products as diagnostic features of the Al Amar group [30].

**Volcanic Unit 3**: Intermediate to felsic pyroclastics (ash-fall, pumice and lapilli tuff), volcanic massive sulfides (VMS), barite and Fe–Mn carbonates.

**Volcanic Unit 4**: Volcanic siltstone, sandstone, crystal tuff and volcanicogenic carbonate.

In addition to these four units, another 5th volcanic unit belonging to the Al Amar Group outcrops outside the area shown in Fig. 3. The Volcanic Unit 5 is dominated by intermediate to felsic pyroclastics [4].

Structurally, the first 3 units were subjected to compressive forces and the first unit represents the footwall of Al Amar deposit. Accordingly, the data revealed from the boreholes indicate horst-dominated paleorelief in units 1, 2 and 3 over which the units 4 and 5 were deposed.

According to extensive drilling programs, Al Amar deposits are classified into (1) volcanic massive to submassive sulfides that are confined to unit 3 and was defined by Ferrand et al. [12] as “stratiform” VMS deposits and as layered VMS deposits by Idris [26] and (2) vein-type deposits traversing units 1, 2 and 3 [4]. In the upper 250 m succession, the mineralized quartz veins (~0.5–0.7 mm stringers and up to 4.5–5 m lodes) are represented by crustified milky quartz with native gold [31,32].

4. Megascopic characteristics of the footwall VMS ore

Beneath the northern vein zone, the present authors collected the VMS samples from a deep level (640 FW-E) in the underground mine. These VMS hand specimens were sampled from Zn-rich zones that dip 72–76° to the NW, and are confined to the unit 3 that is less deformed than its counterpart in shallower depths up to 250–300 m. Due to the rarity of silicic injections and shearing, the Zn-rich ore at the 640 FW-E level shows very minor hydrothermal alteration that are only represented by detached batches of minor sericite and chlorite, if present. The VMS orebody and metapyroclastics of unit 3 are traversed by basaltic dykes.

On the megascopic scale, the massive sulfide ore samples from the investigated level are dominated by sphalerite and relatively lesser amounts of chalcopyrite. When the VMS samples are slightly brecciated or fragmented, they bear some quartz stringers and boudins with common occurrence of megascopic idiomorphic pyrite (~0.2–0.5 mm in dimension). Pyritization can be seen in the fragmented basaltic to andesitic metapyroclastics and sometimes their hand specimens contain up to ~75% pyrite. In contrast to the shallower horizons, the present authors identified no megascopic galena in the VMS of the 640 FW-E level that could be identified by the naked eye. Another characteristic feature of this deep level is the complete absence of exhalative barite, gypsum and anhydrite that are common in unit 3 of the shallower levels [4]. There is no talc alteration in the 640 FW-E level and in one sample only, a ~0.9 mm wide specular-quartz stringer traverse the studied VMS.

5. Procedures and techniques

The authors collected samples from the underground mine at Al Amar using a major vertical shaft at ground surface level of ~900 m a.m.s.l. then the newly explored 640 FW-E level was accessed at depth of ~310 m from the surface. In this underground mine, the vertical distance between nearly horizontal levels is 15 m. Samples were taken in 10 sections representing both floor and ceiling of the level and horizontal interval between each section was 20 m. A complete set of polished mounts and polished thin-sections were prepared for the detailed ore petrographic study using transmitted and ore microscope. The set includes 15 polished mounts and 22 polished thin-sections. Also, 23 thin-sections were studied for the mutual relationship between the ore and the host rocks.

Backscatter imaging and chemical composition of the sulfide minerals and native gold was determined using a JEOL electron-probe microanalyzer JXA-8200 at the
Department of Mineral Resources and Rocks, Faculty of Earth Sciences, King Abdulaziz University, Saudi Arabia. Ore minerals were analyzed for Fe, S, Cu, Zn, Pb, Te, Sb, Bi, As, Au and Ag. Analytical conditions were 20-kV accelerating voltage, 20-nA probe current, 3 μm probe diameter and the counting time was 10 s for each element except for Au and Ag which were 50 and 30 s, respectively. Standards used were pyrite for Fe and S, pure metals for Cu, Au, Ag, Zn, Pb, Te, Sb, and Bi, and gallium arsenide for As. At such conditions, detection limit of gold in the analyzed sulfides was 400 ppm which is equivalent to 0.04%.

6. Paragenesis and ore microfabrics

The modal percentages of sulfide or minerals suggest distinct lateral variation in the contents of the four major minerals; namely sphalerite, chalcopyrite, galena and pyrite that are arranged here with respect to the paragenetic sequence. On scale of 20–30 cm, the percentages of the three minerals vary greatly and each of them dominates over the rest two. Generally, the percentage of pyrite in highly pyritized samples amounts 70–80%, and it is evident that this percentage of pyrite includes the mineral in both VMS sample and its associated quartz veins and stringers. In the silica-poor samples, the VMS ore samples contain up to 65% sphalerite and up to ~50% chalcopyrite. Pyrite in the latter case is a minor component and never exceeds ~10%.

Ore minerals in the host rocks lacking sulfides are represented by high percentage of idioblastic magnetite (60–200 μm wide) that sometimes forms microbands with occasional jasper in few samples. The sulfide-rich host rocks contains up to ~70% ore minerals. In the quartz stringers traversing these sulfide-rich samples, sulfide ore minerals amount 30–35%. The current detailed ore microscopical investigation revealed that the Al Amar 640 FW-E level is rich in sphalerite with chalcopyrite that sometimes reaches a percentage of ~83% in the VMS samples, whereas homogeneous sphalerite amounts as low as 2–3% of the bulk sulfides. Fig. 4 shows the progressive stages of transformation of chalcopyrite disease into banded chalcopyrite–sphalerite ore. This figure documents the perfect alignment of chalcopyrite needles along the two sets of sphalerite cleavages [octahedral (1 1 1) planes] and these needles start to transform into irregular chalcopyrite blebs of different sizes. Finally, microbanding of chalcopyrite in the host sphalerite is resulted.

As mentioned before, the common paragenetic sequence of the studied VMS ore is pyrite(I)–sphalerite–chalcopyrite–galena–pyrite–pyrite(II). Pyrite(I) is the earliest and cracked whereas pyrite(II) is not cracked, idioblastic (50–160 μm wide) and post-dates both sphalerite and chalcopyrite (Fig. 5a). Sometimes, pyrite(I) takes homogeneous sphalerite as inclusions or engulfs crystals that show chalcopyrite disease (Fig. 5b). Massive chalcopyrite fills into the cracks of coarse pyrite (Fig. 5c) whereas tiny chalcopyrite fills the micro-fractures in quartz stringers (Fig. 5d). Galena is microscopic and encloses chalcopyrite and sphalerite but cut by idioblastic pyrite (Fig. 5e and f). Extensive idioblastic pyrite(II) dissemination is recorded in some metabasaltic pyroclastic host (Fig. 6a) where this pyrite is common in the silicified part of this host (Fig. 6b and c). Sometimes, the metabasaltic forms themselves contain few sporadic pyrite crystals (Fig. 6d). Occasionally, the metapyroclastic host shows distinct two generations of pyrite (Fig. 6e). When stringers become more wide (~0.8–0.9 mm), the sulfide ore minerals can be easily seen inside, e.g. chalcopyrite (Fig. 7a and b), translucent homogeneous sphalerite (Fig. 7c), and pyrite (Fig. 7d–f).

The specular-quartz stringers contain typical feather-like hematite (Fig. 8a). The specular hematite invades massive chalcopyrite (Fig. 8b and c) and crystals with chalcopyrite disease (Fig. 8d). Sulfide-bearing quartz stringers and specularite-quartz stringers also invade the mafic dykes. In very rare cases, the stringer becomes wide (~1.7 cm) and quartz shows crustification, comb structure and growth zoning. As a direct indication of compressive deformation, which is lacking on the megascopic scale, few samples show oriented chalcopyrite needles in the chalcopyrite disease. This results in open-folding as seen by curvature of the intergrown chalcopyrite needles either along two sets of cleavage or a single cleavage plane (Fig. 8e and f). Local shearing or uplift could cause such slight deformation.

7. Mineral chemistry of sulfide ores minerals

Three representative samples were analyzed by the electron microprobe for their base and precious metals in addition to sulfur. The obtained data are given in Tables 1–4.

Table 1 shows that chalcopyrite has the highest concentration of gold (up to 1.31 wt%) among the four sulfide minerals in the paragenesis at Al Amar deep footwall (640 FW-E). The studied sphalerite is Fe-poor and this was noticed microscopically because the mineral was translucent in the thin-section. The amount of Fe in the sphalerite lies in the range of 0.17–0.99 wt% (Table 2). Very low content of Co in sphalerite ranges from 0 to 0.02 wt%. Galena is Ag-free but a single grain contains 0.16 wt% Au (SB-13-15) (Table 3). Accordingly, this galena is not argentiferous but slightly auriferous occasionally.

The content of gold in pyrite is also considerable and it amounts up to 1.203 wt% (Table 4). The obtained analyses suggest that there is little substitution for Fe2+ by As3+ and Ni2+. The maximum contents of As and Ni in the analyzed pyrite are 1.35 and 0.131 wt%, respectively. Pyrite(I) is arsenian in which As ranges from 0.71 to 1.35 wt% whereas pyrite(II) is almost free of As, i.e. non-arsenian. In the rest of sulfide minerals, As is also low or absent. It is completely absent in galena whereas it amounts up to 0.029 and 0.02 wt%, respectively in chalcopyrite and sphalerite.

Some submicroscopic native gold inclusions have an average composition of Au93Ag7.

8. Discussion

The ore assemblage, nature of host metapyroclastic rocks and style of mineralization indicate that two VMS ore types can be distinguished: (1) VMS rich in chalcopyrite and sphalerite where both minerals are intergrown and exhibit typical chalcopyrite disease texture and (2) “stringer” ore
Fig. 4. Progressives stages for the transformation of chalcopyrite disease intergrowth into micorbands of chalcopyrite (yellow) and sphalerite (gray). All microphotographs are in polarized reflected light. (a) Perfect orientation of chalcopyrite needles and fine blebs along the (1 1 1) octahedral cleavage of sphalerite. (b) Coalescence of fine blebs and needles into coarser blebs and lamellae. (c) Increase of bleb-sized chalcopyrite and confinement of the chalcopyrite needles to the core. (d) Demolishing of chalcopyrite needles and dominancy of irregular blebs. (e) Advanced stage of irregular chalcopyrite blebs formation. (f) Alternating microbands of chalcopyrite and sphalerite.

Table 1
Electron microprobe analyses of auriferous chalcopyrite.

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Fig. 5. Sulfide microfabrics in VMS and some epithermal quartz stringers. Microphotographs from (a) to (e) are in polarized reflected light. (a) Euhedral pyrite(II) porphyroblasts (Py) disrupting chalcopyrite (Cp) and partially encloses sphalerite (Sph). (b) Sub-idioblastic pyrite(II) (Py) with some sphalerite inclusions (Sph) and engulfment of chalcopyrite–sphalerite (Cp–Sph). (c) Soft slivers of chalcopyrite (Cp) that behaves ductile and protrudes into fractures in coarse pyrite porphyroblast (I) (Py) that practiced plastic deformation. (d) Remobilized chalcopyrite (Cp) ore filling fractures in quartz of the epithermal stringers. (e) BSE image showing euhedrality of pyrite(II) porphyroblasts (Py) that traverse into chalcopyrite (Cp) galena (Gn). (f) BSE image showing fine galena (Gn) at the contact of pyrite(II) porphyroblasts (Py) with chalcopyrite (Cp).

that is characterized by homogeneous sphalerite and common occurrence of pyrite porphyroblasts in crustified and comb-textured milky quartz stringers and few veins. The current data suggest that the remobilized part of the ore in stringers has been formed by open-space filling of fractures (tensile fissures) due to metal redistribution that enhanced by the mobilization of base metals in the VMS ore contemporaneous to greenschist metamorphism and formation of ductile shear planes at the eastern part of the studied level in analogy to similar world examples (e.g. [33]). This level shows complete absence of supergene sulfides that occur at the surface or at shallower levels of Al Amar mine area only [34].

As shown in the chapter of ore microscopy, the textures vary and represent events of slight to moderate brittle and ductile deformation that often characterize the VMS of the Arabian Shield during the Neoproterozoic submarine–subaerial volcanism and formation of volcanic arcs [35]. Usually, textural data provide valuable information about the mineralization history and hence can serve effectively successful exploitation and ore dressing [36]. Ore textural and deformational fabrics of the mineral are so helpful for understanding history of mineralization. In the VMS ore body, the pyrite(II) porphyroblasts are mostly idioblastic (Figs. 5 and 6a and e) and show no evidence of grain annealment, triple junction or “foam texture” that
Fig. 6. Pyrite enrichment of the silicified (in vicinity of quartz stringers) intermediate metapyroclastic host. (a) Dusting by high percentage of idioblastic pyrite(II) (Py), plane polarized light. (b) Considerable amount of pyrite(II) (Py) associating quartz (Qtz) and chlorite-rich fragments (Chl), plane polarized light. (c) Extensive silicification (Qtz) with pyrite(II) (Py) in the pyroclastic with trachybasalt fragments, polarized reflected light. (d) Details of trachybasalt fragment with fine pyrite (Py) inside and some pyrite and chalcopyrite (Cp) outside, polarized reflected light. (e) Two of idioblastic pyrite(II) (Py), polarized reflected light.

indicate directly the absence of any superimposed recrystallization by both regional and contact metamorphism [37]. The studied pyrite porphyroblasts from Al Amar are partially brecciated and the fractures resulted from ductile deformation at the time the surrounding softer sulfides deform by clastic flow mechanism and fill the fractures in pyrite [38,39]. Then, it is evident that the Al Amar pyrite deforms by dislocation creep mechanism at low temperature because if temperature was high, pyrite might deform by dislocation glide [40].

Texturally, the few sulfide-bearing stringers that traverse the VMS main ore body at the Al Amar 640 FW-E level are characterized by homogeneous sphalerite. On the other hand, all of polished mounts from the VMS itself show common occurrence of chalcopyrite disease or chalcopyrite–sphalerite intergrowth. Barton [41] was the
Fig. 7. Sulfide ore minerals in epithermal quartz stringers. (a) Homogeneous chalcopyrite (Cp) in comb-structured quartz (Qtz), crossed nicols. (b) Same as in (a) but in polarized reflected light. (c) Translucent Fe-poor homogeneous sphalerite (Sph) in quartz (Qtz) stringer traversing the metatuff, plane polarized light. (d) Euhedral pyrite (II) (Py) in stringer traversing the metatuff, plane polarized light. (e) Silica microfracture (Qtz) in the metatuff with some pyrite (Py) and finer chalcopyrite (Cp), polarized reflected light. (f) Crustified silica stringer (Qtz) with nearly banded batches of pyrite (Py), chalcopyrite (Cp) and sphalerite (Sph), polarized reflected light.

Table 2
Electron microprobe analyses of Fe-poor auriferous sphalerite.

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Fig. 8. Epithermal specular-quartz stringers and deformation of chalcopyrite disease in the VMS ore. All microphotographs are in polarized reflected light. (a) Specular hematite (Spec) with typical feather-like habit. (b) Quartz (Qtz) and specular hematite (Spec) protruding into microfracture in chalcopyrite (Cp) of the VMS ore. (c) Details of specular hematite (Spec) in chalcopyrite (Cp). (d) Chalcopyrite disease traversed by quartz (Qtz) and specular hematite (Spec). (e) Curvature of chalcopyrite needles and lamellae (yellow) oriented along two cleavage sets in sphalerite (gray). (f) Same as in (e) but curvilinear chalcopyrite is arranged along one set of cleavage.

Table 3

Electron microprobe analyses of Ag-free galena.

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<td>100.43</td>
<td>100.09</td>
<td>101.5</td>
<td>99.14</td>
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first to use the term chalcopyrite disease and stated that it is common in old and modern VMS deposits, black smokers at MOR spreading centers, skarns and epithermal vein deposits, but never occurs in Mississippi Valley-type sulfide deposits. The origin of this intergrowth is greatly controversial and can be formed by a variety of processes such as exsolution crystallization [42], solid-state replacement and diffusion induced segregation reactions [42–44], coprecipitation mechanism [43,45] and in few cases by supergene alteration [46]. The morphology of chalcopyrite inclusions in Al Amar sphalerite host (fine needles and lamellae) is in favor of replacement reaction and atom diffusion rather than an exsolution origin. In addition, the Fe-poor nature of the sphalerite host and presence of irregular bleb-like chalcopyrite inclusions indicate that coprecipitation mechanism also played an important role in the development of Al Amar chalcopyrite disease [43]. Collectively, the factors that influence uptake of Fe by sphalerite include sulfur fugacity and temperature [47]. With high sulfur fugacity, there is an increase of Fe\(^{2+}\) charge compensation for Zn vacancies [48].

The mineral chemistry of sulfides in the Al Amar 640 FW-E level indicates that sphalerite, chalcopyrite, galena and pyrite Au-rich and free submicroscopic inclusions of gold are responsible for high Au content in sphalerite, chalcopyrite and galena [49]. In most pyrite crystals, Au is invisible or lattice bound [50]. Similar world examples of auriferous VMS are characterized by the occurrence of “invisible” gold where Au atoms are concentrated into solid solution within the sulfide structures and do not form discrete or free “visible” gold due to absence or negligible hydrothermal alterations or high-T metamorphism even if Au is low as 0.02 wt% [51]. Translucent sphalerite in thin sections and the EMPA analysis of the mineral are indicative of its Fe-poor nature in which Fe never exceeds 0.99 wt%. The analyzed sphalerite is Co-poor and this suggests that the atomic substitution of both Fe\(^{2+}\) and Co\(^{2+}\) for Zn\(^{2+}\) was very minor. Fig. 9a shows a misleading or an apparent negative correlation between contents of Au and Zn in sphalerite. Actually, the Zn contains is almost constant within error for sphalerite, and then a vertical trend for mechanical mixtures of sphalerite and sub-microscopic gold. Cd is detected spectrally in this Fe-poor sphalerite (not shown in Table 2) which is an indicator of low-temperature crystallization that never exceeds 250–300 °C [52]. Galena is Ag-free similar to that reported by Sharp and Buseck [53] and this suggests single ionic substitution of 2Sb\(^{3+}\) for 3Pb\(^{2+}\) at low-temperature <300 °C instead of the common coupled substitution of Ag\(^{+}\) + Sb\(^{3+}\) for 2Pb\(^{2+}\) if Ag is present as documented by the latter workers. Fig. 9b is a plot of negatively correlated Zn vs. Pb in the galena structure.

Tectonically, volcanogenic massive sulfide deposits in the Arabian Shield and nearby areas are confined either to ophiolite sequences such as the volcanic arcs that have been developed during the Neooproterozoic Pan-African orogeny some 900–550 Ma ago (e.g. [35]). Dubé et al. [54] distinguished two genetic models for Au-rich VMS deposits: (1) conventional syngenetic volcanic-hosted Au-poor VMS mineralization overprinted during regional deformation by Au mineralization and (2) syngenetic

<table>
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<td>0.01</td>
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Table 4
Electron microprobe analyses of auriferous pyrite.
VMS deposits characterized by an anomalous fluid chemistry (with magmatic input) and/or deposition within a shallow-water to subaerial volcanic setting equivalent to epithermal conditions. Tectonic setting, occurrence of epithermal veins and stringers, microfabrics and highly dispersed gold in the Al Amar VMS suggest that the studied auriferous sulfide ore belongs to the second genetic model. Similarly, Hakim and Chinkul [55] affiliated the Au-rich VMS ore at Mahd Adh Dhahab to the second model and they used the tools of fluid inclusions and stable oxygen isotopes to reach the conclusion that the ore has been deposited in shallow depth and represents a typical epithermal deposit. Based on the criteria materialized in the present paper, the authors agree with [29] that Al Amar VMS has some similarities with the Kuroko-type VMS of Japan regardless the age difference. The nature of Al Amar VMS ore and nature of its Al Amar Group host volcanic favor an immature island arc setting [28] which has been argued by [56] to be formed in volcanic arcs that have been developed during the Neoproterozoic Pan-African orogeny some 900–550 Ma ago, and the magma is typically transitional to calc-alkaline [25] in consistency with other world class VMS (e.g. [5,57]). Our megascopic observations, in collaboration with those of [12], support the setting of an immature island arc due to the presence of intercalated chert and marble bands as products of explosive subaerial silicic volcanism and carbonate deposition. Finally, and based on the foregoing discussion, it is believed that studied Al Amar deep sulfide mineralization was affected in parts by structural controls of mineralizations which appear to be confined to post-mineralization and slight to moderate deformation similar to the Wadi Bidah VMS in the Arabian Shield of Saudi Arabia taking in consideration that the latter example is much more deformed.

The megascopic and ore fabrics of the studied VMS and its associated sulfide-bearing epithermal stringers suggest moderate effect of the Najd transcurrent faulting of [58] that appears more effective in the shallower levels in Al Amar gold mine. Hydrothermal jasperoidal chert, extensive shearing, pyrite brecciation, transformation of calcareous bands into talc are good indicators of the Najd effect in the shallower levels of the mine [4,12,23]. The negligible Najd
shear effect in the Al Amar 640 FW-E level was responsible for the lacking of pervasive hydrothermal alterations that are common in shallower levels as well as in the surface outcrops [26].

9. Conclusions

(1) The Al Amar 640 FW-E deep level is characterized by a stratabound VMS deposit with some younger epithermal sulfide-bearing quartz stringers. The paragenetic sequence is pyrite(I)–spalerite–chalcopyrite–galena–pyrite(II). Idioblastic pyrites reach up to ~80% and it shows evidence of plastic deformation by dislocation creep rather than by brittle failure, and relatively softer chalcopyrite almost deforms similarly.

(2) There is a common occurrence of chalcopyrite disease in all samples and galena is identified microscopically only. Owing to its deep horizon, supergene or oxidation sulfide minerals are completely absent.

(3) The transformation of discrete coarse crystals with chalcopyrite disease into “banded” or “stratified” ore is attributed to “local” directive pressure as a deformational expression in low-temperature condition (greenish-facies). The morphology and chemistry of chalcopyrite in Al Amar chalcopyrite disease together suggest a replacement or a coprecipitation mechanism rather than an exsolution from a solid solution.

(4) The VMS is traversed by some epithermal irregular comb-structured or crustified stringers that contain some sulfides in which sphalerite is homogeneous and with complete absence of chalcopyrite disease. Epithermal veining is also represented by few specularite-quartz stringer that crosscut the VMS ore and are possibly co-genetic with the main event that led to the formation of sulfide-bearing quartz stringers.

(5) The EMPA analyses prove that all sulfides in the studied level are Au-bearing and hence the ores are of auriferous nature. Mostly, Au in pyrite is lattice-bound in most whereas high Au values in sphalerite, chalcopyrite and galena are attributed to presence of submicroscopic inclusions of native gold. Galena is abnormally Ag-free. Au content is weakly correlated to Zn in the sphalerite that is Fe-poor where Fe never exceeds 0.99 wt%.

(6) Gold in the Al Amar 640 FW-E level is “invisible” and accordingly, the conventional cyanide leaching techniques would not be feasible. For this reason, the present author recommend gold extraction from the Au-rich sulfides by roasting but this acquires enough energy and water supply for the liberation of free “visible gold”.

(7) Common occurrence of “invisible gold”. Ag-free galena, Fe-poor sphalerite, negligible hydrothermal alteration, pyrite plastic deformation by dislocation creep mechanism and non-exsolution origin of the chalcopyrite disease intergrowth are together strong indicators of low-temperature crystallization (250–300 °C) of VMS or minerals in the Al Amar deep horizons.

(8) The auriferous sulfides in the quartz stringers are epithermal and is not considered as an orogenic gold ore (e.g. [59]) because the fluids were produced after accretion and the waning stage of the Pan-African orogeny during the Late Proterozoic.

Conflict of interest

The authors confirm that no part of this work has been submitted or published elsewhere, and that there are no conflicts of interest.

Acknowledgements

The authors would like to thank the staff of geologists in the Al Amar gold mine, the Saudi Mining Company (Ma‘aden) for their kind field and logistic facilities. Dr. Ahmed Hassan Ahmed is acknowledged for his assistance on the electron microprobe.

References


