Original Article

Ore microscopic characterization of mineralized rocks at the Bi’r Tawilah gold prospect, Saudi Arabia

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\textbf{ABSTRACT}

Ore microscopic investigation of core samples from the Bi’r Tawilah gold prospect enables to distinguish three main groups of ore paragenesis from oldest to youngest, namely magmatic, hydrothermal and supergene. The ore minerals are encountered in sheared and mineralized ophiolitic serpentinites and a variety of hydrothermally altered granitic rocks that include quartz–diorite, granodiorite, monzogranite and quartz–feldspar porphyry. Magmatic ore minerals are chromite, magnetite, ilmenite and pyrrhotite. Hydrothermal ore minerals are the most common (>90%) and they follow the paragenetic sequence: rutile, sphalerite, chalcopyrite, pyrite (with visible gold and electrum inclusions) and arsenopyrite. Supergene ore minerals are ferric Ca-arsenate and ferric oxyhydroxide (±goethite) which represent the weathering products of pyrite and arsenopyrite, respectively. The non-arsenian nature of pyrite and late formation of arsenopyrite all together suggest mobility of As in the hydrothermal fluids until late stages. There are no remarks of ore metamorphism as all events took place post-orogenically despite zonal arrangement of inclusions in pyrite that can result from paucity of crystallization. Ore textures indicate change from early relatively reducing hydrothermal fluids at low \(f_{O_2}\) that crystallize pyrrhotite which is converted into pyrite when the fluid becomes relatively more oxidizing at high \(f_{O_2}\) and \(pH < 5\). On the other hand, the supergene enrichment zone at the uppermost 40 m is dominated by exclusively oxidizing fluids (pH > 7) at low temperature up to \(\sim 75^\circ\text{C}\). Supergene ferric Ca-arsenate is a cellular-structured hydrous phase with distinct \(\text{As}^{5+} \rightarrow \text{Fe}^{3+} + \text{Ca}^{2+}\) ionic substitution in three distinct domains.

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1. Introduction

The Bi’r Tawilah gold prospect is located in the Zalm quadrangle that was mapped in detail by [1]. General studies of lithology and mineral occurrences in the northwest and north-central parts of the quadrangle and in the southwest were carried out. Agar [1] compiled a 1:250,000-scale geologic map of the Zalm area based on a 1:100,000-scale mapping of its six constituted quadrangles by geologists of the DGMR. The earliest works of regional mineral-potential
investigations of the quadrangle is reported in [2]. Then, Collier and Fuchter [3] made an assessment for the sites of ancient gold workings in the same area that were later assessed by [4,5]. Sahl [6] presented additional geologic information and gave a synopsis on possible economic gold mineralization.

The Saudi Gold Mining Company (Ma’aden) launched an extensive exploration program for gold in the Bi‘r Tawilah prospect during the last 10 years and concentrated its drilling activities at the sites close to the Bi‘r Tawilah, Jabal Ghadarah and the satellite prospects of Masarah and Al Mansourah. The main targets are listwaenitized ophiolitic serpentinites that are found along the Tawilah thrust fault zone, in addition to some mineralized quartz–diorite, granodiorite and porphyry rocks. Recent studies of the Bi‘r Tawilah gold prospect [7,8] discussed the distribution of gold and its re-working in a weathered cap due to supergene enrichment. Also, these authors recorded the first known arsenate mineralization in Saudi Arabia which is confined to weathered granodiorite in particular. These arsenates are intimately associated with ferric oxyhydroxides and the precursors are represented by arsenopyrite and pyrite in the hypogene ores at depth.

The present work aims to give the detailed opaque mineralogy of the mineralized rocks from different boreholes in the Bi‘r Tawilah prospect. The samples were collected from different depths (~10–205 m) in order to have a good coverage of both fresh deep and weathered rocks in the uppermost (~40 m). Such a scheme of sampling aims to represent the different ore assemblages which might include those from magmatic to supergene. Besides the ore mineral characterization, the paper presents some microanalytical data of sulfides, gold and hydrous phases in order to verify the microscopic identification and to show the implication on possible substitutions. For this purpose, the ore textures are used here to give information about the evolutionary history of ore mineral paragenesis.

2. Methodology

Ore samples from different boreholes at the Bi‘r Tawilah prospect are first checked for visible sulfide and gold mineralization, and then the core samples are polished as slabs. For the purpose of a detailed ore microscopic study, samples from all mineralized rocks are prepared as polished-mounts for investigation using the reflected-light microscope. In order to check the nomenclature of the different sulfide ore minerals in the studied samples, these minerals are analyzed by scanning electron microscope with an energy dispersive X-ray attachment (SEM-EDX) using a Philips machine Model XL 30 workable at 30 kV accelerating voltage housed at the Central Laboratories of the Egyptian General Authority of Mineral Resources (EGAMR) in Dokki, Egypt. It is safe to get the semi-quantitative EDX analyses of sulfide and gold because it is cheaper, faster and reliable because they are non-hydrous phases. Because some weathered mineralized samples at the Bi‘r Tawilah prospect contain hydrous ore minerals, these phases are analyzed quantitatively by the electron microprobe (EMP) technique using a Jeol JXA8200 machine housed at the Faculty of Earth Sciences, King Abdulaziz University in Jeddah, Saudi Arabia. Operating conditions were 15 kV accelerating voltage, 20 nA probe current, 3 µm beam diameter and 20 s counting time for each element. The standards used are quartz for Si, corundum for AI, pericline for Mg, wollastonite for Ca, zircon for Zr, La-phosphate (LaPO₄) for P and Ga-arsenide (GaAs) for As. For some representative samples with hydrous phases, element distribution maps are prepared by the electron microprobe.

3. Regional geology

In the scope of the modern Proterozoic classification [9,10] stated that most of the Arabian Shield in Saudi Arabia is Cryogenian (850–630 Ma) during which the rocks were developed above subduction zones in a juvenile oceanic environment, deposited in basins above newly amalgamated volcanic arcs and other terranes, or emplaced in the crust during orogeny or as late-tectonic plutons. A large number of the lithostatigraphic units are Ediacaran (630–542 Ma) and resulted from the deposition in intracontinental basins and emplacement of anorogenic plutons, and one unit (mafic plutonic rocks in the core of a magmatic arc), is possibly Tonian (1000–850 Ma). The Arabian Shield in Saudi Arabia and the Nubian Shield in northeast Africa were formed largely by the East African Orogen (EAO) of [11,12] which is an extensive Neoproterozoic accretionary orogen and a major collisional zone within the Gondwana [11,13]. The EAO itself is a part of an orogenic cycle that is related to the breakup of Rodinia (870–800 Ma ago) as reported by [14] until the Cambrian that witnessed the final amalgamation of the Gondwana [15,16]. In the north, the Arabian-Nubian shield that was influenced by the EAO is slightly deformed and metamorphosed if compared with the more strongly deformed high-grade metamorphic rocks in east Africa and the Island of Madagascar.

The Bi‘r Tawilah gold prospect is located at the Zalm quadrangle near the Jeddah-Riyadh highway. The prospect is aligned along N-S ophiolitic serpentinites that are occasionally listwaenitized and intruded by mineralized granitic rocks for which the ore paragenesis are investigated by the present work. The ophiolitic serpentinites in the Bi‘r Tawilah and Ghadarah areas, as well as the intrusive rocks, are low-land exposures that host mineralized rocks in the vicinity of hydrothermal (epithermal) Au–Sn–W-bearing quartz veins [8,17]. Generally, the mineralized zones at the Bi‘r Tawilah prospects are affected by a NW-trending shear zone that is manifested by the Najd shear tectonics, and they are hosted by a variety of granitic rocks that were emplaced along the ophiolite-decorated thrust fault. This is know as “Bi‘r Tawilah thrust fault” which separates two huge arc assemblages known as the Siham and Bani Ghayy groups which started to form before and after the amalgamation of the Afif and Jeddah terranes. The post-amalgamation units are represented by the Murdama, Bani Ghayy, Fatima, and Ablah groups which began to deposit during and soon after the Nabitah orogeny (680–640 Ma) that marked suturing of the Afif terrane with oceanic Arabian-Nubian Shield terranes to the west [18].
4. Geology of the Bi‘r Tawilah prospect

According to the field work and samples from the boreholes, the major Neoproterozoic lithostratigraphic units at the Bi‘r Tawilah gold prospect are represented by Tonian listwaenitized serpentinites as ophiolitic fragments, thick successions of oceanic- and continental-arc associations (Siham and Bani Ghayy groups of Cryogenian and Edicaran ages, respectively), Cryogenian–Edicaran syn-orogenic graniodoids, Edicaran post-orogenic A-type granites and Najd-related dykes (Fig. 1).

The Bi‘r Tawilah prospect area and the surrounding areas are dominated by the Siham and Bani Ghayy groups where they are often found to the east and west of the Bi‘r Tawilah thrust fault, respectively. This fault zone is part of the Nabitah mobile belt or the A‘if terrane suture and separates the Jeddah western terrane from the eastern A‘if terrane [18,19]. The Siham group was deposited above an east-dipping subduction zone in an eastward swallowing basin that grades from deep oceanic (volcanic) in the west and shallow continental margin (sedimentary in the west). It comprises andesite, basalt, rhyolite, shale, lithic sandstone, conglomerate, quartzite and marble. Based on some available isotopic data [10], assigned a middle Cryogenian age to the Siham group (750–685 Ma) and suggested that the Siham-arc magmatism can be divided into older (~754 Ma) and younger (~700 Ma) groups or sub-groups. On the other hand, the Bani Ghayy group consists of sedimentary, volcanioclastic and volcanic rocks that were deposited in pull-apart grabens that post-dated the incipient motion of the Najd system as its fractures were active before and after deposition [20]. The sedimentary rocks are dominated by clast–supported polymictic conglomerates or fanglomerates, sandstone and limestone whereas the volcaniclastics are dominated by welded, lithic and lapilli tuffs that are interbedded with transitional to volcanic conglomerate, and finally ended by flows and sills of porphyritic rhyolite. Radiometrically, the age of the Bani Ghayy group is Edicaran (630–620 Ma) as determined by [21,22]. Lithostratigraphically, the Bani Ghayy group is in part overlapped with the Murdamah group (~655–620 Ma) which is a layered Cryogenian–Edicaran unit that crops out further to the east [10].

The granitic rocks at the Bi‘r Tawilah prospect area obviously intrude the Siham and Bani Ghayy groups but some appears to be contemporaneous to the Siham group and then they are overlain in parts by the Bani Ghayy group. The Siham-related intrusions belong to the Hamal suite of [23] which is dominated by monzogranite and granodiorite. Nevertheless, the Hamal suite at the Bi‘r Tawilah prospect area include intrusions that are contemporaneous to both the Siham and Bani Ghayy groups deposition and this led [24] to divide them into older (~640–625 Ma) Cryogenian–Edicaran calc-alkaline granodiorite to monzogranite, and a younger (~610 Ma) Edicaran alkaline A-type syenogranite to alkali granite.

5. Ore microscopy

This section is devoted to the detailed ore microscopic investigations of mineralized samples that are
brought from the boreholes by the Ma’aden Company. The mineralized rocks are mostly located in a shear zone with remarkable wall-rock alterations and local brecciation [8]. They are ophiolitic serpentinites and granitic rocks where the latter comprise quartz–diorite, granodiorite, monzo-granite and quartz–feldspar porphyry.

5.1. **Ophiolitic listwaenitized serpentinites**

Ore minerals are dominated by magmatic assemblage of Cr-spinel and much lesser pyrrhotite. Chromite is considered as a metamorphic product of serpentinization due to the conversion of magmatic Cr-spinel. This chromite
Fig. 3. Ore paragenesis and paragenetic sequence in quartz–diorite. (a) Hematite-ilmenite (Hem-Ilm) showing partial alteration to titanite (Ttn) at peripheries. P.R.L. (b) Homogeneous magnetite (Mgt) and homogeneous ilmenite that is replaced by a mixture of rutile and titanite (Rt + Ttn). (c) Needle-like aggregate of rutile (Rt) formed due to chloritization of biotite. P.P.L. (d) Interstitial spaces filled by chalcopyrite. P.R.L. (e) Idiomorphic pyrite cube (Py) with coarse and fine silicate inclusions (Sil) that are zonal toward rim. P.R.L. (f) Sub-parallel veinlets of ferric oxyhydroxide (FOH) in highly sheared rock. P.P.L. (g) Visible gold (Au) in pyrite pseudomorphed by ferric oxyhydroxide (FOH), P.R.L.

appears homogeneous and euhedral (Fig. 2a) but in some instances it shows typical cracking along the octahedral [1 1 1] planes (Fig. 2b). Pyrrhotite is fresh and occurs as sporadic subhedral crystals (Fig. 2c). Hydrothermal ore assemblage is mostly pyrite and gold (Fig. 2d) that are in close association with injected silica and carbonates. In some samples, there are obvious K-metasomatism and transformation of serpentine and actinolite into phlogopite which increases with the formation of zoned calcite stringers and veinlets. Formation of phlogopite is
manifested by the nearby granitic intrusions. The felsic fluids that are potassium-enriched lead to the ionic substitution of divalent cations (Ca$^{2+}$ and Mg$^{2+}$) in the structures of both actinolite and serpentine by K$^+$. In such small injections, the wall is lined out with euhedral pyrite (Fig. 2e) whereas the core has radiating arsenopyrite rosette-like crystals (Fig. 2f).

5.2. Quartz–diorite

Magmatic ore minerals in quartz–diorite include homogeneous ilmenite, homogeneous magnetite and hemo-ilmenite (hematite–ilmenite intergrowth). Secondary products of these Fe–Ti oxides suggest that the rock practiced some deuteric alterations where hemo-ilmenite is altered to titanite at peripheries (Fig. 3a) and homogeneous ilmenite to a rutile–titanite mixture (Fig. 3b). Another variety of rutile is formed by a hydrothermal action as biotite practices chloritization (Fig. 3c). Hydrothermal ores in the quartz–diorite also include interstitial chalcopyrite (Fig. 3d) and idiomorphic pyrite with some zonal arrangement of silicate inclusions (Fig. 3e). Supergene minerals are represented by ferric oxyhydroxide that occurs either in the form of sub-parallel veinlets (Fig. 3f) or pseudomorph of hydrothermal pyrite cubes (Fig. 3g). Visible gold is observed in ferric oxyhydroxide that replaces pyrite in the supergene zone (Fig. 3h).

5.3. Granodiorite

In the granodiorite, magmatic ore minerals are only represented by fresh magnetite (Fig. 4a). In the hydrothermal assemblage, it appears that specularite in the sheared samples develops almost at the same time of rutile formation as the structure of biotite collapses. Rutile and specularite are followed in the paragenetic sequence by pyrite and arsenopyrite. Pyrite is idiomorphic and shows uneven distribution of irregular silicate inclusions (Fig. 4b) but occasionally these inclusions are more concentrated at the core (Fig. 4c). Some idiomorphic pyrite shows some sort of zoning (Fig. 4d) which suggests paucity of crystallization from the mineralizing hydrothermal fluids. Arsenopyrite occurs with its typical rhombic outlines and it clearly overprints early rutile (Fig. 4e). Rutile itself occurs as needles or prismatic crystals (Fig. 4f) that are occasionally twinned. Granodiorite contains few gold specks as inclusions in injected quartz (Fig. 4g). Similar to quartz–diorite, granodiorite contains supergene gold in ferric oxyhydroxide (Fig. 4h) whereas arsenopyrite yields supergene ferric Ca-arsenate.

Fig. 4. Ore paragenesis and paragenetic sequence in granodiorite. (a) Fresh homogeneous magnetite (Mgt), P.R.L. (b) Idiomorphic pyrite (Py) showing irregular distribution of silicate inclusions (Sil), P.R.L. (c) Preferential zonal concentration of silicate inclusions (Sil) in idiomorphic pyrite (Py), P.R.L. (d) Sub-idiomorphic zoned pyrite (Py) partly encloses earlier rutile (Rt), P.R.L. (e) Arsenopyrite (Apy) enclosing earlier rutile (Rt), P.R.L. (f) Needles and prismatic crystals of rutile (Rt), P.R.L. (g) Gold inclusion (Au) in injected silica (Qtz), P.R.L. (h) Gold inclusions (Au) in supergene ferric oxyhydroxide (FOH), P.R.L.
Fig. 5. Ore paragenesis and paragenetic sequence in monzogranite. (a) Fresh homogeneous ilmenite (Ilm), P.R.L. (b) Pyrite (Py) replacing pyrrhotite (Po) along weak planes, P.R.L. (c) Pyrite (Py) replaced partly by goethite (Gt) along fractures, P.R.L. (d) Sub-idiomorphic pyrite (Py) showing zonal arrangement of silicate inclusions (Sil) at the peripheral zone, P.R.L. (e) Supergene ferric oxyhydroxide (FOH) with visible gold inclusion (Au), P.R.L.

5.4. Monzogranite

Fresh homogeneous ilmenite (Fig. 5a) and magnetite are common magmatic ore minerals in the monzogranite whereas the hydrothermal ore minerals are rutile, pyrrhotite and pyrite. Textural evidence suggests earlier formation of pyrrhotite which is then followed by either partial or complete transformation into pyrite. This
transformation obviously proceeds along cracks and cleavage planes (Fig. 5b). Cracks of pyrite itself contain goethite as a product of hydration (Fig. 5e). Some sub-idiomorphic pyrite crystals show zonal arrangement of rutile and silicate inclusions (Fig. 5f). Again, supergene visible gold is recorded in weathered monzogranite as inclusions in ferric oxyhydroxide (Fig. 5g).

5.5. Quartz–feldspar porphyry

Homogeneous ilmenite, as a magmatic mineral, shows peripheral alteration to titanite (Fig. 6a) in the quartz–feldspar porphyry. The rock contains the same hydrothermal ore assemblage of monzogranite with just few differences. The porphyry rock contains abundant pyrite (Fig. 6b) that reaches up to ~75% of the total opaque percentage. Arsenopyrite is idiomorphic, rhombic (cross-sectional) or prismatic (longitudinal) as shown in Fig. 6c. Idiomorphic arsenopyrite includes oriented traces of earlier rutile needles (Fig. 6d). Hydrothermal interstitial violet fluorite is also present (Fig. 6e). In the weathered porphyry rocks, supergene minerals are goethite and ferric oxyhydroxide that display perfect colloform texture (Fig. 6f).

6. BSE images and other accessory minerals

The studied Bi’r Tawilah mineralized granitic rocks possess some typical igneous (magmatic) accessories that can be identified both microscopically and by the BSE imaging and microanalysis. Locations of some spot analyses in Tables 1 and 2 are given in Fig. 7.

Fig. 7a–d shows the occurrence of primary thorite and monazite crystals, euhedral six-sided apatite and euhedral zircon, respectively. Hydrothermal pyrite often contains inclusion of zircon (Fig. 4d) or much finer earlier hydrothermal sphalerite and chalcopyrite (Fig. 7e and f, respectively). The BSE image (Fig. 7g) supports the ore microscopic investigation of hydrothermal assemblages which indicate transformation of pyrrhotite into pyrite. Also, another BSE image (Fig. 7h) for a weathered sample indicates that pyrite is altered to ferric oxyhydroxide whereas arsenopyrite is altered to ferric Ca-arsenate in the supergene enrichment zone.

7. Microchemistry of ore and other accessory minerals

Table 1 gives some representative microanalyses of hydrothermal ore minerals and gold. Because of its
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<td>76</td>
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<td>41.31</td>
<td>40.95</td>
<td>41.40</td>
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<tr>
<td>Fe</td>
<td>58.69</td>
<td>59.05</td>
<td>58.60</td>
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<td>68</td>
<td>84</td>
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<tr>
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<td>21.58</td>
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<table>
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<td>98.38</td>
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<tr>
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–, not detected.
common Fe deficiency as the chemical formula implies (Fe_{1-x}S), pyrrhotite contains lower Fe than in pyrite (44.53–47.53 wt% and 58.60–59.05 wt%, respectively). No arsenic is detected in the analyzed pyrite so it is arsenic-free or non-arsenian. No traces of lattice-bounded Au are also detected. Table 1 informs that arsenopyrite and chalcopyrite have their typical compositions without any noticeable traces. On the other hand, it is clear that sphalerite is Fe-bearing where Fe amounts to 8.39 wt%. Spot analyses of gold in Table 1 suggest that it is either native gold or electrum. The latter contains Ag in the range of 5.34–27.19 wt%. Gold outside pyrite is ultra-pure but when it is enclosed in pyrite it yields some analyses with up to 6.40 wt% Fe due to incorporation of some iron from the background (Fig. 8).

Owing to their hydrous nature, some EMPA of ferric Ca-arsenate (FCA) and ferric oxyhydroxide (FOH) are given in Table 2. These analyses and element distribution map shown in Fig. 9 suggest that there is a common ionic
Fig. 8. SEM-EDX spectra, BSE images and microanalyses of electrum and ultra-pure gold. (a) Electrum inclusion in pyrite (Py) that partly encloses rutile (Rt). Electrum composition is given (see also analysis # 61, Table 1). (b) Coarse gold (Au) of nearly equal size to zircon (Zrn). Ultra-pure gold composition is given (see also analysis # 67, Table 1).

substitution \((\text{As}^{5+} \leftrightarrow \text{Fe}^{3+} + \text{Ca}^{2+})\) in three domains of FCA where CaO and As2O5 perfectly decrease as Fe2O3 increases toward the dark domain. FOH is slightly arsenian with 1.21–1.32 wt% As2O5. Fig. 9 suggests even distribution of trace P, Zr and S in both FCA and FOH. The rest of analyses in Table 2 are for other accessory minerals that are shown in Fig. 7. Apatite bears some traces of Fe whereas thorite has considerably high As2O3 content (10.99–15.38 wt%).

Monazite is typically REE-bearing (La, Ce and Nd) and occasionally bears some Sm (2.11 wt% Sm2O3).

8. Discussion

The complete absence of As in the crystal structure of analyzed pyrite (Table 1) classifies the mineral as a non-arsenian pyrite and that all As is incorporated in
arsenopyrite which is younger in the paragenetic sequence. This suggests that As was mobile in the mineralizing hydrothermal fluids at the Bi’r Tawilah until they become relatively oxidizing. The chemistry of Bi’r Tawilah As-free pyrite indicates that the mineral is neither $\text{As}^1\text{–pyrite}$ [25,26] nor $\text{As}^3\text{–pyrite}$ [27,28]. The non-arsenian nature of the Bi’r Tawilah pyrite is also supported by some EMPA cited in [8] where As is very minor (0.01–0.06 wt%). This suggests that visible gold in ferric oxyhydroxide in the supergene zone was not originally invisible or lattice-bound. Normally, invisible gold is common in As-rich pyrite, and only when As is positively correlated with Au [29]. The investigated hydrothermal ore assemblage of Bi’r Tawilah shows some evidence of shear continuation after deposition which result in brecciation and strain shadow in few pyrite crystals. It is believed that this hydrothermal
assemblage practiced no metamorphism as the age of some mineralized rocks is post-orogenic such as the A-type quartz–feldspar porphyry. In this respect, it is stressed here that zonal arrangement of inclusions in pyrite is hence not an evidence of metamorphism [30] but it simply results from paucity of crystallization. Irregular shape and uneven distribution of inclusions in the Bi’r Tawilah’s pyrite are other strong evidence that a metamorphic event after the hydrothermal activity is lacking.

The detailed ore microscopic investigation of the Bi’r Tawilah sulfide-rich samples indicates a common transformation of pyrrhotite into pyrite. Such type of transformation is documented experimentally by [31] where pyrrhotite is commonly converted to pyrite and marcasite at hydrothermal conditions up to 220 °C. This means that the characteristic of the mineralizing fluids at the Bi’r Tawilah prospect changed with time from relatively reduced conditions and relatively low fS2 which led to crystallization of pyrrhotite to oxidizing ore-forming fluids with relatively high fS2 which enabled pyrite to replace pyrrhotite. In natural sulfide ore assemblages, this conversion occurs normally at pH <5 [32]. Previous investigation by [8] suggested the conversion of few pyrite into pyrrhotite at the Bi’r Tawilah samples from the boreholes but this seems hard to occur because such reverse type of conversion requires both metamorphic conditions after ore deposition and presence of organic matter [30,33–35] and these are completely lacking in the case of Bi’r Tawilah.

In their detailed study that concerns with weathering of the Bi’r Tawilah sulfides in granodiorite [7], documented the common alteration arsenopyrite into a yokumite-like alteration mixture that comprises ferric calcium arsenate (FCA) and arsenian oxyhydroxide (AOH) whereas pyrite is altered to ferric oxyhydroxide (FOH). The same features are recorded here in the present work and it is believed that oxidation took place at elevated pH (>7) and temperature up to ∼75 °C. The availability of Ca2+ and high pH buffered by the dissolution of calcite in the marble, in addition to the prevailing temperature upon weathering, played important roles in the formation of these pseudomorphs at the Bi’r Tawilah prospect [7]. The processes thought to explain the release of As from minerals in the bedrock include oxidation of arsenian pyrite or arsenopyrite, or carbonation of As-bearing sulfides and desorption of As by the surface Fe–oxyhydroxide [36]. Oxyhydroxides are amorphous or nano-crystalline phases that are either hydrogenic or hydrothermal [37] but the case of Bi’r Tawilah is exclusively pedogenic as products of weathering. Similarly, Fe-Mn oxyhydroxides were reported in weathered felsic volcanic rocks [38].

9. Conclusions

Magmatic ore paragenesis in the serpentinites prior to ocean floor metamorphism are Cr-spinel (now chromite) and pyrrhotite whereas they are homogeneous ilmenite, hemo-ilmenite and homogeneous magnetite in the granitic rocks. Hydrothermal alterations in terms of listwaenitization of serpentinites lead to formation of pyrite and gold while the deuteric-hydrothermal alterations of granitic rocks alter ilmenite into rutile, titanite and alter magnetite.
to specularite particularly in more sheared samples. Hydrothermal ore paragenesis represents >90% of total ores in the Bir Tawilah mineralized samples and they are arranged chronologically from oldest to youngest as follows: rutile, sphalerite, chalcoprite, pyrite (with visible gold inclusions) and arsenopyrite. Gold is either native or electrum with up to 27.19 wt% Ag. Due to weathering, some supergene ore minerals are formed (ferric Ca–arsenate and ferric oxyhydroxide).

Pyrite is non-arsenian with no invisible gold, and it forms at the expense of pyrrhotite as the mineralizing hydrothermal fluids change from relatively reducing to low $f_O^2$ to more oxidizing at high $f_O^2$ and pH < 5. Supergene ferric Ca–arsenate is a cellular–structured hydrous phase with distinct As$^{5+}$ ↔ Fe$^{3+}$ + Ca$^{2+}$ ionic substitution, and it forms from exclusively oxidizing fluids (pH > 7) at temperature up to ~75°C.

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.

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