The Bi’r Tawilah deposit, central western Saudi Arabia: Supergene enrichment of a Pan-African epithermal gold mineralization

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The Bi’r Tawilah gold deposit in central western Saudi Arabia represents a Pan-African example of gold mineralization in which both hypogene and supergene ores are recorded. The sulphidic gold ore is hosted in intermediate to felsic intrusions that occur along the N–S trending thrust-fault zone within the so-called “Nabtah orogenic zone”. There are four rock units present (from oldest to youngest): serpentinites and related listwaenites, diorites, granitic rocks and porphyries. Hydrothermal alteration consists of chloritization, sericitization, carbonatization and silicification and affects all rock types. Chloritization of biotite results in abundant rutil, whereas sulphidization coincides with carbonatization. The Bi’r Tawilah ore is confined to NW-trending shears (Riedel fractures) related to N–S slip of the pre-existing Tawilah thrust due to activation within the Najd fault system. Samples from the boreholes show macro- and microscopic evidence of shearing such as micro-shear planes and strain shadows of pyrite. Sulphides and gold are present in most rock types. Paragenetically, the sulphides consist of abundant pyrite and relatively lesser amounts of arsenopyrite, in addition to very minor chalcopyrite, sphalerite and galena. In all boreholes, it was noticed that the abundance of arsenopyrite increases with depth.

The elevated silver content of electrum (13–22 wt%) at Bi’r Tawilah is typical of gold deposits and low-sulphidation epithermal deposits. The early mineralization stage took place in proximity to hydrothermally altered intermediate to felsic intrusions. The aerially restricted hydrothermal alteration by carbon-aqueous fluids led to ore remobilization in which gold amounts up to 4.3 g/t. Finally, gold enrichment (up to 5.4 g/t) resulted from supergene alteration that took place during weathering above the water table at a depth of 20–25 m.

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1. Introduction

Gold mineralization in the late Proterozoic Pan-African Arabian–Nubian Shield is of great interest for understanding the relationship of ore genesis and tectonics of the orogeny. In the Nubian Shield in Egypt and northern Sudan, gold mineralization in the Pan-African belt has different genetic types where the noble metal is encountered in different lithologies (e.g. carbonated ultramafics, gabbro-granite contacts, exhalative volcanic and associated VMS) that are all characterized by multiple metal sources (e.g. Surour et al., 2001; Kusky and Ramadán, 2002; Zoheir, 2008, 2011; Gabr et al., 2010). Recently, gold has been of particular interest for exploration and mining in the Arabian Shield of Saudi Arabia. Gold occurrences in the Arabian Shield are widespread and most of these occurrences are known as sites of old workings developed on gold-bearing quartz veins, gossans and, rarely, placers (Botros, 2004). Some of these gold occurrences are ranked as ore deposits of economic significance and have been mined or are under evaluation, e.g. Mahd Ad Dahab, Sukhaybarat, Bulghah, Al Hajar, Jadmah, Hamdah, Ad Duwayhi and Bi’r Tawilah by the Saudi Mining Company (Ma’aden) and the Shayban prospect (CITADEL, 2008, 2009) (Fig. 1).

Primary gold mineralization in the Arabian shield can be grouped into three main types based on tectonic settings and host rocks (Harbi et al., 2006). The first type is associated with volcanosedimentary sequences (e.g. the Siham Group or the early Hulyfah Group), including volcanicogenic massive sulphide deposits (VMS) and epithermal base- and precious-metal deposits. Gold in some of the VMS deposits may have been re-worked by the Najd Fault System (transcurrent deformation, Fleck et al., 1976) where epi-thermal mineralizations are associated with some massive sulphide deposits (e.g. Mahd Ad Dahab and Al Amar). The gold-bearing zones at Al Hajar gold mine were subjected to some
supergene enrichment processes and gold was enriched in the oxidation zones that almost lack any sulphides. Dubé et al. (2007) distinguished two genetic models for Au-rich VMS deposits: (1) conventional syn genetic volcanic-hosted Au-poor VMS mineralization overprinted during regional deformation by Au mineralization; and (2) syngenic 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. Lack of detailed mineralogical and microfabric studies for the Saudi VMS-related gold deposits does not allow researchers to affiliate them to one or both of the genetic models of Dubé et al. (2007). Recently, Mercier-Langevin et al. (2010) defined in their review a geometric mean gold grade for 513 VMS deposits worldwide of 0.76 g/t, and deposits with more than 3.46 g/t Au (geometric mean plus one geometric standard deviation) are considered auriferous. This latter category also includes some examples from Saudi Arabia such as the Nuqrah deposit with a gold grade of 3.80 g/t Au.

The second type of gold deposits is spatially associated with carbonatized ophiolitic ultramafic rocks (listwaenites), which

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**Fig. 1.** General geologic map of the Arabian Shield showing major tectonostratigraphic terranes, ophiolite belts, sutures, fault zones, post-accretionary basins in the Arabian Shield of western Saudi Arabia (from Nehlig et al., 2002 with modifications by Johnson and Woldehaimanot, 2003; Stern and Johnson, 2010). Numbers represent locations of the major gold deposits as follows: (1) Hamdah, (2) Al Hajar and Jadmah, (3) Mahd ad Dhahab, (4) Jabal Shayban, (5) Humaymah, (6) Bulghah, (7) Sukhaybarat, (8) Al Amar, (9) Ad Duwayha, (10) Um Matierah, (11) Ar Rjum, (12) Ash Shakhkaliya, (13) Zalm, (14) Bi'r Tawilah (including Jabal Ghadarah, Al Mansourah and Masarah).
decorated the suture zones during the amalgamation of the different terranes. Listwaenites are widespread and have been identified and described from different suture zones: Nabitah, Al Amar, Bi’r Umq and Yanbu (Al Shanti, 1993). Currently, the Saudi Ma’aden mining company explores the Bi’r Tawilah area in the central part of the Arabian shield; e.g. Al Mansourah and Masarah. Gold mineralization associated with listwaenite is a promising target for current and future exploration along the Nabitah suture zone in the western provinces in the Aff composite terrane (Harbi et al., 2006).

The third type of the gold deposits is particularly abundant in the western parts of the Aff terrane to the east of the Nabitah suture zone, where late- to post-tectonic (640–610 Ma) diorite–granite plutons and/or their subvolcanic equivalents intruded the Murdama and Bani Ghayy groups, e.g. Sukhaybarat, Zalm, Bulghah, Bi’r Tawilah, Ad Duwayhi and Jabal Ghadarah (Collenette and Grainger, 1994; Nehlig et al., 1999; Leistel et al., 1999; Al Jahdli, 2004; Doebrich et al., 2004). These deposits have been described by Agar et al. (1992) as structurally and/or magmatically controlled mesothermal vein-type gold mineralization formed in intraplate settings. In this case, the gold mineralization is quartz veins and stringers where gold mainly occurs as free microscopic specks along fractures of pyrite, arsenopyrite and occasionally chalcopyrite. These deposits are characterized by low sulphide minerals content, typically associated with arsenopyrite, pyrite and/or pyrrhotite, and were deposited from CO2-rich ore fluids (Al Jahdli, 2004; Harbi et al., 2006). The role of these intermediate to felsic intrusions whether they were the source of the mineralizing fluids or the source of heat which initiated meteoric water convection and leaching of gold from the country rocks or both is still debatable. The intrusions were emplaced after terrane amalgamation (~670 Ma). Gold was mined from the oxidation zone in some of these deposits, e.g. Bulghah and Sukhaybarat.

During the 1980s, gold mineralization in carbonated ultramafic outcrops or listwaenites in the Bi’r Tawilah (Figs. 1 and 2) received some attention, e.g. Labbé (1984), Billa (1987) and Couturier (1988) especially for the outcrops at Jabal Ghadarah, some 4 km
west of the Bi‘r Tawilah main prospect. Current exploration and drilling programs are focused, however, on granitoids and porphyries. The present work aims to distinguish the different stages of mineralization that possibly range from magmatic to hydrothermal activities and finally to supergene alteration. Our study also tries to establish a paragenetic sequence of ore and gangue minerals, and finally discusses the genetic interpretations of the Bi‘r Tawilah gold mineralization.

2. Geologic set up of Bi‘r Tawilah area

The Arabian–Nubian Shield (ANS) consists of a juvenile Neoproterozoic crust that represents an area of suturing between East and West Gondwana before the Paleozoic (Johnson et al., 2011). It formed through accretion of numerous inter-oceanic island arcs along ophiolite-decorated suture and gneissic fault zones between 900 Ma and 550 Ma when the Mozambique ocean closed (Stern, 1994). This took place much earlier than the opening of the Red Sea, 30–25 Ma ago (Camp and Roobol, 1992) during which the ANS was divided into the Arabian and Nubian Shields. In the framework of the terrane model given by Johnson (1999, 2003), the Bi‘r Tawilah area is located along the so-called “Ad Dafinah thrust” that separates the Afif terrane in the east from the Jeddah terrane in the west. The Bi‘r Tawilah area (Figs. 2 and 3) is located on the eastern side of the Nabitha suture zone west of the Afif terrane. The latter was defined by Stoesser and Camp (1985) as a complex assemblage consisting of volcanic-arc sequences and a microplate of older crust that are overlain by ~710 Ma volcanosedimentary sequences in deep basins (Doebrich et al., 2004). Initially, the Afif terrane was termed as Zalm terrane (Johnson and Vranas, 1984). Schmidt et al. (1979) and Stoeser and Camp (1985) indicated that the orogenic belt of the Nabitha suture defines a 100–200 km wide zone of crustal deformation, remobilization and plutonism. The belt is characterized by linear complexes of synorogenic gneissic to massive granitic rocks, separated by regions of amphibolite- to middle greenschist-grade metamorphic rocks mostly of the volcanosedimentary sequence of the Hulyfah or Siham Group, the younger metasedimentary rocks of Bani Ghay Group and the ophiolitic mafic–ultramafic rocks which mark the suture zone between the Afif terrane and the western arc terranes (Stoesser and Camp, 1985).

In the Bi‘r Tawilah area (Figs. 2 and 3), the early and late Hulyfah volcanosedimentary sequences, namely the Siham and Bani Ghayy Groups in chronological order are located to the east and west of a major thrust fault. They are flysch-type sediments while the younger molasse-type volcanosedimentary rocks are known as the Mirdumah Group (Viland, 1986). Doebrich et al. (2004) studied the younger syn-orogenic rocks (granodiorite and rhyodacite porphyry) of the Hamal batholith and assigned a 710–685 Ma SHRIMP U/Pb zircon age for them.

The Bi‘r Tawilah area contains ancient gold and tungsten mine workings (Fig. 3) close to a N-striking thrust fault which is part of the Nabitha suture zone. This thrust fault is decorated by the listwaenized serpentinites of the Arabian Peninsula (Buission and Leblanc, 1985, 1987) and separates the Bani Ghayy Group in the west from the Siham Group in the east (Saber and Labbé, 1986). However, Al Jahdli (2004) in accordance with Villand (1986) used the term distal facies (early Hulyfah or the Siham Group) for the rocks exposed to the east of the fault. The Siham Group consists of highly foliated and deformed chlorite, sericite and hornblende ortho-schists while the Bani Ghayy Group consists of conglomerate, greywacke and siltstone intercalated with pyroclastics and metabasalts. Both the Siham and Bani Ghayy Groups were subjected to greenschist-lower amphibolite facies metamorphism (Al Jahdli, 2004). The rocks exposed at Jabal Bani Ghayy were considered by Agar (1988) to consist of ortho-schists and a part of the molasse-type sediments.

The volcanosedimentary rocks of the Siham and Bani Ghayy Groups (~620 Ma and ≥690 Ma, respectively; Stacey and Agar, 1985) were intruded by syn- to late-orogenic and post-orogenic intrusive rocks. Accordingly, the Bi‘r Tawilah thrust fault is younger than 620 Ma, and therefore coincides or post-dates the third major event of the Nabitha suture that consists of three episodes: 710–680–640 Ma (Quick, 1991). The syn- to late-orogenic intrusive rocks that mostly occur to the east of the Bi‘r Tawilah fault and locally in the central part range in composition from diorite to granodiorite. According to Al Jahdli (2004) the syn-orogenic intrusive rocks are represented by highly weathered, fractured and locally
sheared diorite and granodiorite that are exposed to the east of Bi‘r Tawilah at Jabal Ghadarah along the contact between listwaenitized serpentinite and the late Hulyah Group rock varieties. It was found that the granodiorite contains pyrite and arsenopyrite disseminations that are gold-bearing (Al Jahdli, 2004). Several types of syn- to late-orogenic intrusive rocks including porphyritic and fine-grained granite and porphyry-granodiorite were described also by Saber and Labbé (1986).

The post-orogenic intrusive rocks (Haml suite) occur as large batholiths (Fig. 2), mostly to the north and east of Bi‘r Tawilah and are represented by Jabal Al Awjah monzogranite truncating the northern extension of the Bi‘r Tawilah fault. The age of the plutons belonging to the Haml batholith ranges from 659 ± 7 Ma (Doebrich et al., 2004) to 651 ± 12 Ma (Agar et al., 1992). Late NW-trending aplastic microgranite dykes cross-cut the volcanosedimentary rocks of the Siham Group and the syn- to late-orogenic intrusive rocks. These dykes host the Bi‘r Tawilah W mineralization (Saber and Labbé, 1986).

Previous studies believed that the so-called “Najd Fault System” played an important role in the genesis of gold in the Bi‘r Tawilah and other deposits in the Arabian Shield. According to Johnson et al. (2011), the extent of Late Cryogenian–Ediacaran Najd–north-west-trending transcurrent fault system in the Arabo-Nubian Shield and surrounding areas makes it one of the largest shear systems known on Earth. In their review, Johnson et al. (2011) stated that the Najd shears range from single, linear faults to broader sets of shears. Movement was predominantly sinistral, although the offset of some plutons and inferences about the origin of some Jibalah Group pull-apart basins suggest local dextral slip (Cole and Hedge, 1986; Agar, 1987; Matsah and Kusky, 2001; Kusky and Matsah, 2003). The shears chiefly trend NW to NWW, but a small number of NE-trending dextral shears such as the Ad Damm fault zone are believed to be conjugate shears for the Najd system (Davies, 1984).

3. Methods and techniques

The studied core samples were collected from several boreholes of a current diamond drilling program by the Saudi Ma‘aden Mining Company at the Bi‘r Tawilah. The ore minerals, as well as the gangue minerals and mutual relationships, were first studied using both transmitted and reflected light microscopy. Prior to the stage of electron microprobe, the well representative samples were investigated by using the SEM-EDS technique for more detailed identification of minerals, textures and microstructures. A Philips scanning electron microscope with energy dispersive X-ray attachment (SEM-EDX) Model XL 30 was used at the Central Laboratories of the Egyptian Mineral Resources Authority of Egypt. Working conditions are 30 kV accelerating voltage, 15–20-nA probe current and 5 μm beam diameter.

Chemical composition of the sulphide 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, 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, Bi, and gallium arsenide for As. At, such conditions, detection limit of gold in the analyzed sulphides was 400 ppm which is equivalent to 0.04%. Gold content in the whole-rock samples (g/t) was determined by the fire assay technique at Al Amri Laboratories, Jeddah, Saudi Arabia; where the detection limit was 0.01 ppm.

4. Gold at the Bi‘r Tawilah deposit

Exploration for gold is currently in progress by the Saudi Mining Company (Ma‘aden) in three sites. The first is close to the Tawilah water well (Bi‘r Tawilah), whereas the other two localities (Al Mansourah and Masarah) are located farther south. The main lithological units underlying the Bi‘r Tawilah area are mafic volcanoclastic of the Siham group, conglomerate and sandstone. These rocks are deformed by N–S thrust structure, namely the Bi‘r Tawilah fault zone. There are limited exposures of granodiorite, and much lesser diorite, at the surface. The exposures of granodiorite increase northwards until being well represented at Jabal Ghadarah. The sole good exposure in the area is 55–120 cm thick barren quartz veins that trend NW, NE and E–W which are the main three shear components of the regional fault system. This goes in harmony with structural data obtained by Agar (1988) who analyzed the movement vectors of the Najd fault system at the Zalm quadrangle including the Bi‘r Tawilah deposit area.

For the last five years, the Saudi Ma‘aden Mining Company launched an exploration program for gold and associating noble metals at the area to the south of Bi‘r Tawilah. The program concentrated exploration at two locations, namely Al Mansourah and Masarah. The main aim of the extensive diamond drilling was gold in carbonatized ultramafics or listwaenites. The present study focuses on the area to the south of the Bi‘r Tawilah where the boreholes indicate that the main lithologies are little ophiolitic serpentinite (particularly at depth), diorite, granitic and porphyry intrusions. The granitic rocks include massive and slightly deformed granodiorite and monzogranite. The late quartz-feldspar porphyry intrusions are identified at some boreholes (e.g. BTWC-028 and BTWC-031) at depths of ~58 and 197 m below surface. These rocks contain 4–10% sulphide minerals, but locally attain up to ~20% in porphyries, with the exception of some quartz-feldspar porphyry from the drillhole BTWC-031 that has no sulphides but with feldspar radioactive mineralization. This variety of porphyries (at depth of ~197 m) could be related to the W-bearing post-orogenic granites in the area of study that have been identified earlier by Saber and Labbé (1986). At the surface outcrops as well as in borehole BTWC-031, Sn–W mineralization is confined to a series of east-trending radioactive fluorite-bearing quartz veins and stringers (Saber, 1983). The cross-cutting relationships suggest a younger age of Sn–W mineralization as it overprints the gold-bearing zones in hydrothermally altered diorite and garnodiorite. Feybesse and Le Bel (1984) concluded that the Bi‘r Tawilah Sn–W mineralized dykes and veins have typical REE patterns of specialized granites and considered the Awjah microgranite as the probable parent pluton of such mineralization. It can be added here that the radioactive fluorite-bearing quartz-feldspar porphyries in the boreholes are equivalent to the microgranite at the surface.

Concerning samples of the weathered (supergene zone) obtained from the Bi‘r Tawilah boreholes it is evident that diorite is highly weathered and has barren quartz stringers (Fig. 4a). Some diorite samples are hydrothermally altered and then subjected to weathering (Fig. 4b). The granodiorite shows different degrees of weathering (Fig. 4c and d). Even the porphyries are weathered as indicated by oxidized pyrite (Fig. 4e).

5. Petrography

At Bi‘r Tawilah gold prospect, the encountered rock types obtained from the boreholes are serpentinite, diorite, granitoids and felsic porphyry intrusions. The ophiolitic serpentinites are traversed by ~3 cm thick banded carbonate veins. The vein displays sharp contact with the
ultramafic rock. The diorites are mostly microdiorite or medium-grained variety that are sheared, silicified and hydrothermally altered at depth up to ~200 m. On the other hand, diorites in the weathered horizon show superimposed supergene alterations on the earlier hydrothermal alteration. Carbonate minerals in the vein include coarse calcite crystals that show banding, interlocking and idiomorphism towards the vein centre. Coarse comb-structured calcite crystals cut diorite and show distinct growth zoning and associate idiomorphic pyrite at their rims. The coarse carbonate captures "fish-like" microscopic enclaves of metasomatized serpentinite. K-metasomatism in the serpentinites is represented by alteration of actinolite and tremolite to phlogopite due to soaking of the ultramafic lithology by magmatic-hydrothermal fluids coming from beneath that are related to the post-orogenic granites in the area such as the monzogranite.

The diorite is melanocratic and consists of amphiboles and plagioclase, in addition to chlorite as the common alteration (secondary) mineral. The amphiboles are represented by hornblende and much finer actinolite. Some hornblende crystals have dense black core and some others exhibit both simple and lamellar twinning. Actinolite occurs as short rods that are altered to chlorite especially in the sheared parts. Along micro-shear planes, the diorite is highly sericitized. Locally, the rock is silicified where secondary quartz is coarse and anhedral. This quartz is strained, fractured and traversed by very thin veinlets of silica and carbonates. Where altered diorite is weathered, the rock becomes darker and Fe-oxides and hydroxides are common. Hydrothermal biotite is very common as interstitial phase and not as a primary mineral. Also, coarse silica veinlets are present containing elongated layers of quartz perpendicular to the wall of fractures. Along micro-shear planes, carbonatization is more pronounced.

On textural basis, the granodiorite is either non-porphyritic or porphyritic. It shows distinct shearing, brecciation, hydrothermal alteration and finally weathered products rich in sercite, kaolinite and Fe-oxhydroxide. In the granodiorite, plagioclase is altered to sericate flakes oriented along cleavage planes. Sometimes, the sericite shows perfect alignment along the plagioclase twinning lamellae. The plagioclase rim is almost sericite-free as sericitization is selective at the core. Carbonate veinlets sometimes show bifurcation and invade altered plagioclase and quartz with fluid inclusions. Biotite is altered to chlorite and rutile. All of the investigated granodiorite samples contain zoned zircon crystals that are rimmed with radioactive pleochroic haloes against the biotite flakes. The monzogranite contains two generations of plagioclase that is commonly sericitized. Biotite is highly kinked due to deformation, altered to rutile and chlorite. Biotite occurs as aggregates that contain different kinds of inclusions such as apatite, rutile and radioactive zircon.

In the late porphyry intrusions, euhedral plagioclase occurs as phenocrysts that contain biotite inclusions and altered to sercite particularly at the core. Coarse biotite is altered to sercite and rutile. Inclusions in biotite are apatite and zircon. The porphyries are traversed by 0.3–0.7 cm thick quartz stringers that are rich in idiomorphic pyrite and arsenopyrite.

Fig. 5 illustrates some distinct hydrothermal alterations in the deep horizons such as chloritization of biotite and rutile formation (Fig. 5a and b). Carbonatization is common in the form of sub-parallel veinlets (Fig. 5c and d).

6. Ore paragenesis and paragenetic sequence

A summary for ore mineral paragenesis in the main five rock types (serpentinites, diorite, granodiorite, monzogranite and porphyries) is given in Fig. 6.
The oldest rock type at the deep levels (~190–205 m) is represented by serpentinites as the sole ophiolitic component. Ore minerals in the serpentinite are either orthomagmatic (chromite and pyrrhotite) or hydrothermal (pyrite and native gold). The serpentinite is rich in highly brecciated ferrichromite which is much coarser than pyrrhotite. Both fine pyrite and gold dust in the serpentinite are only confined to the silicified parts of the rock where the silica veinlets cross-cut magmatic pyrrhotite.

In the diorite, magmatic Fe–Ti oxides are represented by ilmenite and lesser amounts of magnetite. The percentage of ilmenite is approximately equal to that of the hydrothermal sulphide ore minerals. Ilmenite is either homogeneous (altered to hematite, rutile and coarse titanite) or homogeneous in the form of hemo-ilmenite exsolution intergrowth.

Two distinct episodes of pyritization are suggested, namely disseminated and hydrothermal pyrite. The first one produced disseminated pyrite in non-deformed diorite and granodiorite at Bi'r Tawilah as well as at Jabal Ghadarah (Al Jahdli, 2004). Diorite and granodiorite at depth (up to 155 m) are intensively sheared and hydrothermally altered. Some of the coarse hydrothermal pyrite shows distinct strain effects as evidence of shearing. This strained pyrite is distorted and develops "pressure shadow" made up of strained quartz. In few cases, deformation of the host rocks leads to limited brecciation of the sulphide as well. Upon weathering, the altered sheared diorite becomes a reddish rock characterized by schistose-like texture and common occurrence of ferric oxyhydroxides where invisible gold in the pyrite structure is converted into visible gold. In few instances, chalcopyrite inclusions are encountered in both pyrite and arsenopyrite in the sheared diorite.

The granodiorite is characterized by frequent aggregates of rutile that displays two habits, needle-shaped and massive and results from alteration of magmatic ilmenite. Subordinate flaky specularite develops at the expense of magnetite. Pyrite occurs as inclusions in arsenopyrite or as euhedral pyrite crystals with rutile inclusions. Arsenopyrite starts to crystallize at the late stages of hydrothermal pyritization and it continues until the former cross-cut the latter. Fine-grained gold occurs at the contact between pyrite and arsenopyrite or as inclusion in the earlier pyrite only. Similar to the case of diorite, supergene ferric oxyhydroxides develop visible gold due to the oxidation of pyrite upon weathering.

In the monzogranite, pyrite occurs as idiomorphic crystals that display distinct growth zoning by zonal arrangement of rutile and silicate inclusions. Very few visible gold inclusions occur in pyrite at the depth of ~55 m. The highly weathered rocks near the surface bear also some gold specks.

Primary Fe–Ti oxide minerals in the feldspar and quartz-feldspar porphyry intrusions are lacking, but hydrothermal minerals are common instead. The latter comprises pyrite and fluorite. At
depth greater than 175 m, the porphyry contains high amount of pyrite (up to 20%). Flourite occurs as violet interstitial phase. In the weathered samples, pyrite in porphyries is commonly oxidized to goethite comparable with ferric oxyhydroxides in the other previously described weathered rock types.

Fig. 7 illustrates some of the common ore minerals and textures in the Bi’r Tawilah mineralized rocks at depths. Pyrite is common as idiomorphic crystals (Fig. 7a). Idiomorphic pyrite crystals contain some inclusions of microcline and other silicates (Fig. 7b). Strained pyrite with pressure shadow is common in the sheared rocks (Fig. 7c). Pyrite is commonly developed along fractures associating colloform calcite (Fig. 7d). Arsenopyrite occurs in its typical rosette-like habit associating coarse banded calcite veining, even in the oldest rock type or the serpentinites (Fig. 7e). Cross-sections of rhombic arsenopyrite are common and post-date rutile (Fig. 7f). Arsenopyrite post-dates the event of partial to complete conversion of pyrite to arsenopyrite (Fig. 7g). Finally, some idiomorphic arsenopyrite contains inclusions of rutile, chalcopyrite and pyrite supporting the observation that arsenopyrite is the latest sulphide phase in the paragenetic sequence (Fig. 7h).

Also, the BSE images support the observations obtained from the ore microscopic investigation. In the weathered samples, gold occurs along fractures and growth zones of colloform-structured ferric oxyhydroxide (Fig. 8a and b). Chalcopyrite is earlier than...
pyrite, pyrrhotite and arsenopyrite. Chalcopyrite veinlets are over-printed by idiomorphic pyrite and pyrrhotite (Fig. 8c). In the deep zones (65–135 m), fresh samples contain visible gold inclusions in pyrrhotite (Fig. 8d).

7. Gold geochemistry and mineral chemistry

During the early phases of exploration at Bi‘r Tawilah, the Ma‘aden Mining Co. carried out some ICP analyses of some trace elements in addition to the fire assay data of gold. Fig. 9, which is a courtesy of the Ma‘aden Co., shows the variation of such elements in both weathered zone (~40 m thick) with supergene alterations and the deep zone with hydrothermal alteration as well. It is evident that gold increases in the weathered zone which goes in harmony with the ore microscopic investigation supported by the BSE images and mineral spectra. It is important to notice that regardless of the degree of weathering, hydrothermal gold stands as the responsible cause of the precious element enrichment. This can be easily noticed in Fig. 3c and d where the less weathered granodiorite bears much more gold (2.52 g/t) than the least weathered granodiorite (0.90 g/t) at the same borehole. Accordingly, amount of hydrothermal gold is an important controlling factor before being more concentrated by weathering. This figure shows some enrichment of Cu, Cr and Ni in the weathered zone whereas no obvious variations in the contents of Pb and Zn can be noticed. Arsenic defines an irregular trend due to its erratic distribution in both weathered and fresh deep zones which is controlled by introduction of arsenopyrite almost in all rock varieties.

Fire assay data of the different host rocks varieties from the boreholes are given in Table 1. The table shows that gold in the sheared serpentinites at depths from 195 to 203 m averages 0.127 g/t. This might be attributed to the presence of fine sulphides in the silica-carbonate alteration of the ultramafics in analogy to similar Pan-African ophiolitic serpentinites in the Eastern Desert of Egypt (Zoheir and Lehmann, 2011). Al Jahdli (2004) observed K-metasomatism in some surface outcrops of serpentinites at the Bi‘r Tawilah and reported similar gold content comparable to that we had obtained from borehole samples. Our metsomatized serpentinites from the borehole (BTWC-04) show evidence of biotite formation at the expense of actinolite. As to the diorite, gold increases in the weathered samples which contains up to 5.401 g/t. Some hydrothermally altered diorite at depth of ~155 m contains up to 4.285 g/t Au owing to the presence of native visible gold in pyrite and interstitial quartz, particularly in the silicified samples. In contrast to diorite, both granodiorite and monzogranite samples contain lesser gold content in the weathered zone amounting 1.881 and 2.517 g/t, respectively. Weathered porphyries contain the least gold content amounting 0.057 g/t.

Gold is relatively concentrated in the weathered rock zone (e.g. BTWC-006). Locally, gold is much higher in the deep zones of a neighbouring borehole, only 25 m apart (e.g. BTWC-079). On the other hand, gold is enriched at shallow depths in neighbouring boreholes (e.g. BTWC-004 and BTWC-073). In the former, gold varies in the range of 0.53–1.18 g/t for some ~17.25 m thick intersections. In the latter, there is a supergene zone following ~1 m thick gravel and sand with an average gold content of 0.57 g/t followed by a narrow 2 m with 0.33 g/t Au. Details of gold content in the borehole BTWC-006 give some useful information where the weathered granodiorite bears 1.03–1.15 g/t Au with remarkable enrichment in the brecciated granodiorite in the supergene zone (1.33–2.46 g/t). In the deep zone, fresh granodiorite contains remarkably high gold content in the range of 2.92–12.73 g/t being invaded by ~30 cm thick quartz veins. The quartz veins assayed maximum gold of 1.68 g/t suggesting that much of their gold is transported into the adjacent granodiorite.

Gold and different sulphides were analyzed using the electron microprobe technique and the averages of about 103 spot analyses are given in Table 2. The table shows that gold in both weathered and deep samples contains considerable amount of Ag amounting 12.73% and 21.99%, respectively. Such analyses suggest that gold inclusions in pyrite from fresh deep horizons are Ag-rich and can be considered as “electrum”.

![Figure 8. EDX backscatter images (BSE) of gold and some sulphides and their inclusions. All are taken for samples from borehole BTWC-006.](image-url)
Pyrite contains the highest gold content (0.17–0.34%) compared to other sulphide minerals; e.g., arsenopyrite (0.18–0.25%) and pyrrhotite (0.14–0.16%) as given in Table 2. Also, sphalerite and chalcopyrite inclusions in the Fe–As sulphides are auriferous, and their gold content amount 0.20–0.31% and 0.18–0.21%, respectively. On the other hand, galena is Au-free but it bears considerable content of Ag (averaging 0.71%). Galena has some impurities of Te and Sb amounting up to 0.145% and 0.215%, respectively. Te and Sb in pyrite, pyrrhotite and arsenopyrite are negligible (up to 0.01% and 0.04%, respectively).

Table 1
Gold content in the Bi’r Tawilah boreholes intersecting weathered and deep zones.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Depth</th>
<th>Rock name</th>
<th>Horizon</th>
<th>Au content (g/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Serpentinite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-1</td>
<td>197.00–198.00 m</td>
<td>Sheared serpentinite</td>
<td>Deep</td>
<td>1.881</td>
</tr>
<tr>
<td>4-2</td>
<td>194.00–200 m</td>
<td>Micro-diorite</td>
<td>Deep</td>
<td>0.004</td>
</tr>
<tr>
<td>7-4</td>
<td>39.70–40.15 m</td>
<td>Altered diorite</td>
<td>Deep</td>
<td>0.390</td>
</tr>
<tr>
<td>7-7</td>
<td>155.00–156.35 m</td>
<td>Altered diorite</td>
<td>Deep</td>
<td>4.285</td>
</tr>
<tr>
<td>7-8</td>
<td>181.00–182.90 m</td>
<td>Altered diorite</td>
<td>Deep</td>
<td>0.004</td>
</tr>
<tr>
<td>7-2</td>
<td>31.85–32.15 m</td>
<td>Highly sheared diorite</td>
<td>Deep</td>
<td>1.310</td>
</tr>
<tr>
<td>7-6</td>
<td>145.90–146.90 m</td>
<td>Highly sheared diorite</td>
<td>Deep</td>
<td>0.244</td>
</tr>
<tr>
<td>4-00</td>
<td>21.40–21.50 m</td>
<td>Altered diorite</td>
<td>Weathered</td>
<td>5.401</td>
</tr>
<tr>
<td>61-1</td>
<td>8.00–8.10 m</td>
<td>Altered diorite</td>
<td>Weathered</td>
<td>0.819</td>
</tr>
<tr>
<td>38-1</td>
<td>6.30–7.00 m</td>
<td>Highly sheared diorite</td>
<td>Weathered</td>
<td>0.662</td>
</tr>
<tr>
<td>(b) Diorite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-0</td>
<td>14.00–14.15 m</td>
<td>Granodiorite</td>
<td>Weathered</td>
<td>1.881</td>
</tr>
<tr>
<td>15-1</td>
<td>10.80–10.90 m</td>
<td>Brecciated granodiorite</td>
<td>Weathered</td>
<td>0.900</td>
</tr>
<tr>
<td>31-2</td>
<td>9.30–9.40 m</td>
<td>Granodiorite</td>
<td>Weathered</td>
<td>0.338</td>
</tr>
<tr>
<td>7-5</td>
<td>121.00–122.00 m</td>
<td>Porphyritic granodiorite</td>
<td>Deep</td>
<td>0.004</td>
</tr>
<tr>
<td>7-1</td>
<td>191.00–193.00 m</td>
<td>Monzogranite</td>
<td>Deep</td>
<td>0.024</td>
</tr>
<tr>
<td>4-0</td>
<td>7.00–7.15 m</td>
<td>Brecciated monzogranite</td>
<td>Weathered</td>
<td>0.739</td>
</tr>
<tr>
<td>8-1</td>
<td>17.00–17.15 m</td>
<td>Monzogranite</td>
<td>Weathered</td>
<td>1.967</td>
</tr>
<tr>
<td>15-2</td>
<td>20.00–20.10 m</td>
<td>Monzogranite</td>
<td>Weathered</td>
<td>2.517</td>
</tr>
<tr>
<td>26-1</td>
<td>17.40–17.50 m</td>
<td>Monzogranite</td>
<td>Weathered</td>
<td>0.153</td>
</tr>
<tr>
<td>28-3</td>
<td>197.40–197.50 m</td>
<td>Porphyritic monzogranite</td>
<td>Deep</td>
<td>0.045</td>
</tr>
<tr>
<td>(c) Granitic rocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-1</td>
<td>58.10–58.30 m</td>
<td>Feldspar porphyry</td>
<td>Deep</td>
<td>0.011</td>
</tr>
<tr>
<td>31-1</td>
<td>197.40–197.50 m</td>
<td>Quartz-feldspar porphyry</td>
<td>Deep</td>
<td>0.009</td>
</tr>
<tr>
<td>34-1</td>
<td>9.90–10.00 m</td>
<td>Quartz-feldspar porphyry</td>
<td>Weathered</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Fig. 9. Variation of gold and some trace elements in weathered and fresh horizons at borehole BTWC-001, Bi’r Tawilah prospect.
The element distribution map of some elements in pyrite transformed to pyrrhotite from fresh granodiorite (BTWC-006) shows enrichment of arsenic at the rim (Fig. 10). Element distribution map of some elements in some sulphides from fresh granodiorite (BTWC-006) shows homogeneity of pyrrhotite and arsenopyrite (Fig. 11).

### Table 2
Average EPMA composition of the analyzed ore minerals from the Bi’r Tawilah mineralized zones. (Concentrations are in wt%, \( n = \) number of points analyzed, n.d = not detected.).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Pyrite</th>
<th>Arsenopyrite</th>
<th>Pyrrhotite</th>
<th>Chalcopyrite</th>
<th>Sphalerite</th>
<th>Galena</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample(^a) No.</td>
<td>28-4 ((n = 1))</td>
<td>6-7 ((n = 13))</td>
<td>28-4 ((n = 4))</td>
<td>6-5 ((n = 3))</td>
<td>6-6 ((n = 22))</td>
<td>28-4 ((n = 9))</td>
<td>6-5 ((n = 10))</td>
</tr>
<tr>
<td>As</td>
<td>0.06</td>
<td>0.01</td>
<td>40.78</td>
<td>39.89</td>
<td>42.21</td>
<td>0.09</td>
<td>0.48</td>
</tr>
<tr>
<td>Fe</td>
<td>54.50</td>
<td>60.06</td>
<td>32.43</td>
<td>37.12</td>
<td>35.38</td>
<td>46.65</td>
<td>48.03</td>
</tr>
<tr>
<td>S</td>
<td>41.02</td>
<td>39.49</td>
<td>22.36</td>
<td>22.95</td>
<td>21.31</td>
<td>50.83</td>
<td>51.36</td>
</tr>
<tr>
<td>Zn</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Cu</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Te</td>
<td>0.02</td>
<td>0.01</td>
<td>n.d</td>
<td>n.d</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Pb</td>
<td>0.14</td>
<td>0.02</td>
<td>2.82</td>
<td>0.01</td>
<td>0.60</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Au</td>
<td>0.34</td>
<td>0.17</td>
<td>0.25</td>
<td>0.24</td>
<td>0.18</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>Sb</td>
<td>0.03</td>
<td>0.01</td>
<td>n.d</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Ag</td>
<td>0.01</td>
<td>n.d</td>
<td>n.d</td>
<td>n.d</td>
<td>n.d</td>
<td>n.d</td>
<td>n.d</td>
</tr>
<tr>
<td>Total</td>
<td>96.18</td>
<td>99.79</td>
<td>98.77</td>
<td>100.27</td>
<td>99.72</td>
<td>97.84</td>
<td>100.06</td>
</tr>
</tbody>
</table>

\(^a\) 6-1 = weathered granodiorite, 6-5 = fresh granodiorite, 6-6 = fresh brecciated granodiorite, 6-7 = fresh slightly deformed monzogranite and 28-4 = fresh quartz-feldspar porphyry.

Fig. 10. Element distribution map of some elements in pyrite transformed to pyrrhotite from fresh granodiorite (BTWC-006) showing enrichment of arsenic at rim. Notice that the bright chalcopyrite inclusions are Au- and Ag-free.

8. Discussion
In analogy to the Zalm, Bulghah and Sukhybarat prospects in the Nubian Shield of Saudi Arabia, the Bi’r Tawilah gold mineralization is suggested to be intrusion-related (e.g. Nehlig et al., 1999; Sahl et al., 1999) where the host rocks comprise diorite, granodiorite and...
granite. On the other hand, Al Jahdli (2004) and Harbi et al. (2006) suggested an epigenetic hydrothermal origin at the Bi’r Tawilah prospect, specifically at Jabal Ghardarah. The latter authors attributed the enrichment of the late-orogenic granodiorite in gold and sulphides to leaching from listwaenites that decorate the Nabitah suture zone along which the Bi’r Tawilah gold deposit is located. Based on ore microscopic investigation, the present work suggests that primary magmatic sulphides are negligible at the Bi’r Tawilah granodiorite as well as associating diorite and monzogranite that are not hydrothermally altered. In collaboration with the current detailed mineralogical, microstructural and fire assay data, we suggest here the Riedel fractures of a N–S slip faulting system acted as important structural conduits for channeling the hydrothermal fluids. During the early phase of the Najd orogeny, there was initiation of pretectonic phase of fracture propagation, igneous emplacement and graben formation that was controlled by dextral shear in a NW-trend (Moore, 1979). Based on detailed structural analysis, Agar (1988) demonstrated that the volcanosedimentary rocks of the Bani Ghayy Group at the Bi’r Tawilah deposit area were deformed by transcurrent movements along faults of the same Najd trend but displacement becomes sinistral and not dextral, and finally sinistral displacements of all structures by the late phase of the Najd fractures reactivation. The youngest fractures controlled the emplacement of post-tectonic plutons (e.g. Awjah granite and quartz-feldspar porphyry) and dyke swarms as the final stage of the Najd strike-slip movement (Agar, 1988). The latter author showed that the orientation of the Riedel fractures at the Bi’r Tawilah area are very characteristic in a sinistral shear zone proximal to the Hami plutonic suite to the east of the Tawilah Fault Zone.

In the fresh deep horizon, ore microscopic investigations suggest that rutile is the first mineral to be crystallized in the ore paragenesis which is then dominated by sulphides. The paragenetic sequence of sulphide ore minerals in a single epigenetic mineralization stage: chalcopyrite (along with minor sphalerite and galena) → pyrite → arsenopyrite, where arsenopyrite increases with depth. In the supergene zone at Bi’r Tawilah prospect, sulphides are decomposed and replaced by an assemblage of semi-crystalline to amorphous arsenates and Fe-hydroxides. According to a recent mineralogical study on the arsenate mineralogy at Bi’r Tawilah gold prospect, Surour et al. (2013) suggested that pyrite in the weathered horizon is pseudomorphed by ferric oxyhydroxide, whereas arsenopyrite is oxidized to an intrasratified phase of arsenian ferricyanide and Ca–Fe arsenate similar to yukonite. Sulphides are represented by nearly equal amounts of pyrite and arsenopyrite. Detailed investigation of microfabrics suggests that the sulphides were introduced to the host rocks after the late stages of solidification, i.e. connected to magmatic-hydrothermal system characterizing the intrusion-related gold deposit. The history of mineralization suggests early crystallization of pyrite that is subjected to brecciation as the strength of shearing increases (Fig. 12a). Such deformation facilitates also the development of sub-parallel fractures along which pyrite and arsenopyrite were deposited associating calcite in veinlets (Fig. 12b and c) where the carbonate is colloform mostly. In some few instances, these sulphides form thin veinlets along irregular or intersected fractures (Fig. 12d). If the Bi’r Tawilah sulphide-rich samples belong to an intrusion-related deposit hosted by diorite and granodiorite, presence of interstitial pyrite (Fig. 12e and f), as well as along

Fig. 11. Element distribution map of some elements in some sulphides from fresh granodiorite (BTWC-006) showing homogeneity of pyrrhotite (Po) and arsenopyrite (Apy). Notice that gold (Au) bears noticeable silver content.
fractures, favours an epigenetic rather than intrusion-related style of mineralization at the Bi'r Tawilah gold deposit. The post-orogenic alkaline monzogranite and feldspar porphyry are younger in age than the syn- to late-orogenic calc-alkaline diorite and granodiorite in the area of study (Agar et al., 1992). Anomalous gold content in least altered granodiorite (up to 12.78 g/t) is attributed to interstitial auriferous sulphides that are connected to nearby mineralized quartz stringers and stockworks that supports again an epigenetic origin. Gold content in the quartz veins themselves never exceeds 1.68 g/t suggesting that the precious metal is transported to the adjacent lithologies by post-injection leaching kinematics (Harbi et al., 2006).

There are some world examples in which gold is associated with Sn–W–Mo–Sb–Cu–Bi mineralization. Genesis of some examples is explained in terms of a porphyry model (Galley and Franklin, 1985) and in some other cases the origin of W is not clear with probabilities of derivation from the magma directly or from the adjacent skarn and metasedimentary country rocks by the hydrothermal fluids. In most of these examples, Sn–W-bearing quartz veins pre-date the gold precipitation in the same granitic pluton (Maloof et al., 2001; Kesler et al., 2003; Mikulski, 2011). This is an opposite model to the case of Bi'r Tawilah because our observations document the cross-cutting relationships of much younger Sn–W-bearing quartz veins connected to the Awjah micrograitae which was also accepted earlier by Feybesse and Le Bel(1984). Hence, the Au-bearing quartz veins at the Bi'r Tawilah traverse the hydrothermally altered diorite and porphyritic granodiorite which are older than the albite microgranite and its Sn–W quartz veins.

9. Conclusions

The Bi'r Tawilah area is a part of the Neoproterozoic N–S trending Nabitah belt (Greenwood et al., 1976; Gass, 1977; Roobol et al., 1983). According to Letalenet and Bounny (1977) and Agar (1988) both the Siham and Bani Ghayy Groups were formed at structural grabens during the Nabitah and Najd orogenies (D2 and D3), respectively. In a later stage, these successions were intruded by diorites and post-orogenic granites that host some gold mineralization at the Zalm and Bi'r Tawilah prospects.

(1) Most rocks at Bi'r Tawilah boreholes are hydrothermally altered (chloritized–sericitized–carbonatized–silicified). Chloritization of biotite resulted in abundant rutile whereas the crystallization of sulphide minerals is contemporaneous with a phase of carbonatization. The earliest pyrite generation occurs in the form of accessory magmatic disseminations.

(2) Evidence of shearing that include conjugate fractures, microshear planes and strain shadows in pyrite. On the basis of structural analysis, all of them are resultant of prominent northwest-trending strike-slip faults of the so-called “the Najd fault system” that is dated back to 680 Ma (Johnson, 1996) until 530 Ma (Stacey and Agar, 1985). The observed shear structures at the mineralized zone of Bi'r Tawilah are merely fractures and do not seem to be parts of trough-going shear zone.

(3) Based on the ore mineralogic investigation, it is concluded that sulphides and gold are present in most rock types at the Bi'r Tawilah deposit. Sulphides in the serpentinites are...
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