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Metallogeny of gold in relation to the evolution of the Nubian Shield in Egypt

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Abstract

Gold mineralization in the Eastern Desert of Egypt is confined, almost completely, to the basement rocks of the Nubian Shield that was cratonized during the Panafrican orogeny. Island-arc, orogenic and post-orogenic stages are indicated for the tectonic-magmatic evolution of the Nubian Shield in Late Proterozoic times. Different styles of gold mineralization recognised in the Eastern Desert are inferred to have developed during these stages. In the island-arc stage, which is characterized by volcanic and volcaniclastic rocks in an ensimatic environment, gold mineralization is hosted in stratiform to strata-bound Algoma-type BIF and associated tuffaceous sedimentary rocks. Both types represent exhalative deposits, formed during breaks in sub-marine basaltic and bastalic–andesite volcanic eruptions. The volcanic rocks have a tholeiitic affinity and reflect an immature arc stage. Gold hosted in massive-sulphide deposits within calc-alkaline rhyolites represents another style of gold mineralization connected with mature island arc stage. During the orogenic-stage, ophiolites and island arc volcanic and volcaniclastic rocks were thrust onto the Pre-Panafrican continental margin. Subduction was active beneath the continent while the thrusting was still operative. A phase of calc-alkaline magmatic activity developed during this stage and the compressional deformation event was synchronous with regional metamorphism (greenschist–amphibolite facies). Extensional shear fractures (brittle–ductile shear zones) were broadly contemporaneous with the intense compressional tectonic regime. These fractures opened spaces in which the mineralizing fluids penetrated. Gold mineralization associated with the orogenic-stage is represented by vein-type mineralization that constituted the main target for gold since Pharaonic times. Other styles of gold mineralization during this stage are represented by altered ophiolitic serpentinites (listwaenites), Gold mineralization associated with intrusion related deposits (possibly porphyry copper deposits), as well as, auriferous quartz veins at the contacts of younger gabbros and G-2 granites. The post-orogenic stage is characterized by the dominance of intra-plate magmatism. Small amounts of the element in disseminations, stockworks and quartz veins of Sn–W–Ta–Nb mineralization represent gold mineralization connected with this stage. The link between these tectonic–magmatic stages and gold mineralization can be used as a criterion at any exploration strategy for new targets of gold mineralization in Egypt. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Upper Proterozoic; Nubian Shield; Panafrican belt; Gold mineralization

1. Introduction

The Eastern Desert of Egypt was long known as a mining district for gold since ancient times with more than 90 locations spread over the whole area covered by the Precambrian basement rocks (Fig. 1). Gold-mining records range back to predynastic times and continued at different periods. During the period 1902–1958, the Nubian Shield produced about 7 tons of gold (Kochine and Basyuni, 1968). In most mines,

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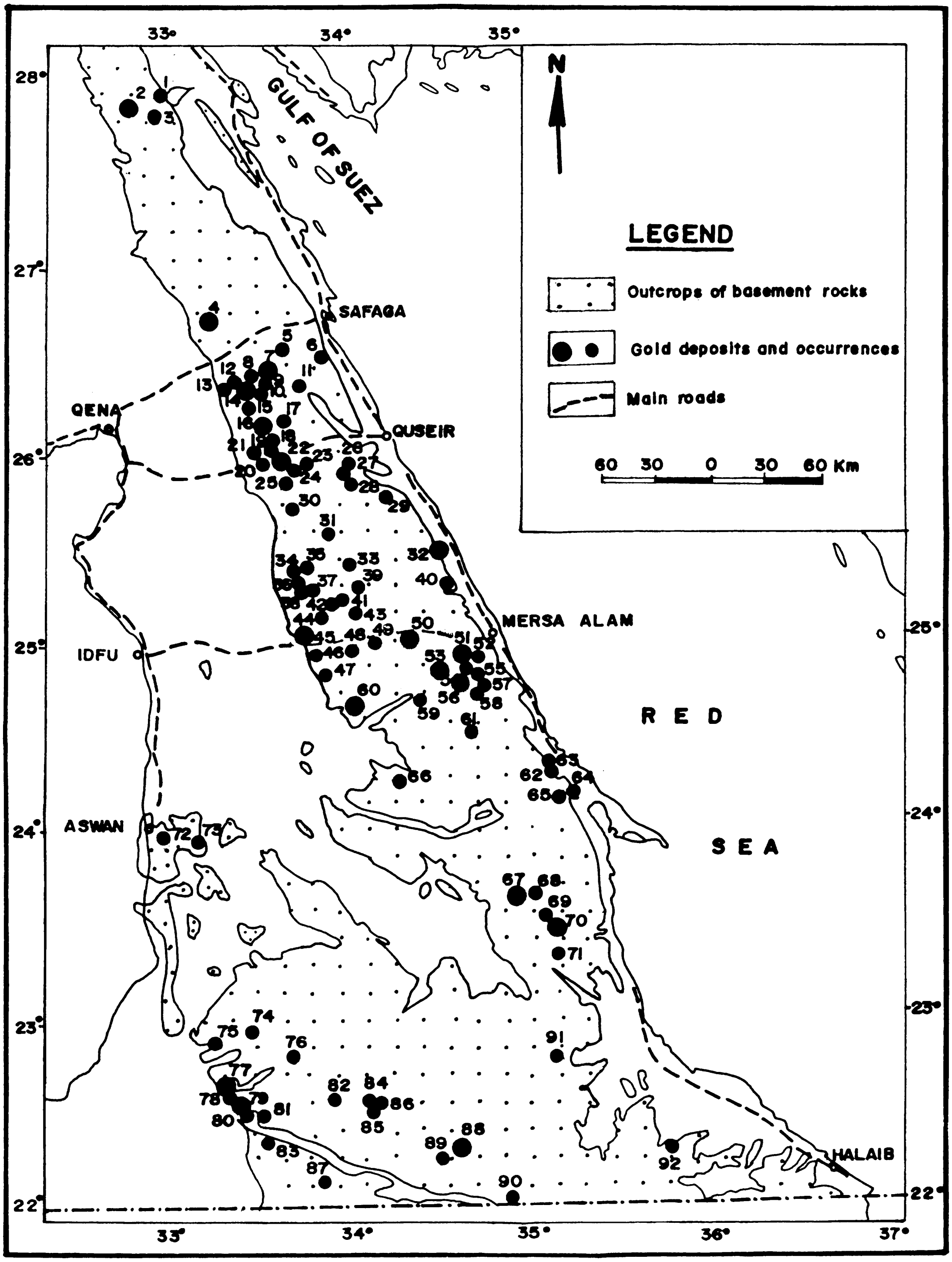
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LEGEND
Outcrops of basement rocks
Gold deposits and occurrences
Main roads
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the ancient Egyptians extracted gold from quartz veins of various dimensions in open-pit and underground workings. At present, no production is coming out and activities are concerned on the evaluation of the old gold mines and tailings.

Timing of gold mineralization in Egypt is controversial. Two approaches prevail: one theory interprets gold mineralization as integral part of hydrothermal processes related to dioritic intrusions of Metarchean (Proterozoic) age (Hume, 1937) or related to the Gatterian granites of Late Proterozoic–Early Paleozoic age (Amin, 1955; El Shazly, 1957). The other theory maintains that gold mineralization is multi-aged and related to general tectonic–magmatic stages (Sabet et al., 1976). Recently, Botros (1991, 1995b) suggested that gold mineralization in Egypt is multi-aged and genetically associated with volcanic cycles that repeatedly occurred in the Nubian Shield from the Precambrian to the Tertiary.

The well-known spatial and temporal relationship of gold mineralization to tectonic structures in the Nubian Shield (Loizenbauer and Neumayr, 1996), combined with the recent recognition of the importance of plate tectonic process in the Precambrian (Dardir and Greiling, 1987; Dardir et al., 1990; Greiling and Rashwan, 1994), raises the important question of how gold mineralization fits into the plate tectonic evolution of the Nubian Shield. Understanding the timing of gold mineralization in the structural evolution of the Panafrican belt in the Nubian Shield could lead to improved exploration criteria. Despite the fact that gold deposits and occurrences were long under exploitation, and that they were discovered, rediscovered, examined and investigated many times, they are insufficiently studied (El-Ramly et al., 1970). The present paper, is thus, the first one that attempts to correlate the different episodes of gold mineralization in the Eastern Desert with the major tectonic–magmatic stages that characterize the evolution of the Nubian Shield.

2. Evolution of the Nubian Shield in Egypt

The basement rocks of the Eastern Desert of Egypt constitute the Nubian Shield that has formed a continuous part with the Arabian Shield in the Arabian Peninsula before the opening of the Red Sea. It is generally accepted that the basement of the Nubian Shield was cratonized during the Panafrican orogeny around 570 Ma ago (El Gaby et al., 1988).

The Precambrian basement complex of Egypt comprises about 10% of the total area of the country. It is exposed mainly in the Eastern Desert along the Red Sea, in the southern portion of Sinai and locally in the Western Desert (Fig. 2). In the Eastern Desert, the basement rocks extend as a belt parallel to the Red Sea Coast for a distance of about 800 km hosting all known locations of gold deposits in Egypt.

The term "Pan-African" was introduced by Kennedy (1964) to define an "important and widespread tectonic and thermal event" which affected the African continent during the Late Precambrian and Early Paleozoic, some 500 ± 100 Ma ago. However, the term was later used by Gass (1977) to describe the whole process of cratonization of ocean arc complexes and their collision and welding to the older African craton during the time period 1200–450 Ma.

The evolution of the Nubian Shield was interpreted in terms of the classical geosyncline and mountain-building cycles, which dominated the geological thinking for many years (Akaad and El Ramly, 1960; Sabet, 1961; El Shazly, 1964). During this period, most work-

Fig. 1. Gold deposits and occurrences in the Eastern Desert of Egypt (compiled from Kochine and Basyuni, 1968). (1) Umm mongul; (2) Umm Balad; (3) Wadi Dib; (4) Fatira; (5) Abu Marawat; (6) Wadi Gasus; (7) Semna; (8) Gebel Semna; (9) Abu Qarahish; (10) Kab Amiri; (11) Sagi; (12) Gidami; (13) Hamama; (14) Erediya; (15) Abu Had; (16) Atalla; (17) Rebshi; (18) Umm Esh; (19) Fawakhir; (20) Hammamat; (21) Umm Had; (22) EL Sid; (23) Umm Selimat; (24) Hammuda; (25) EL Nur; (26) Kareim; (27) Kab EL Abyad; (28) Tarfawi; (29) Sherm ELBahaari; (30) Zeidum; (31) Wadi Zeidum; (32) Umm Rus; (33) Sigdit; (34) Talat Gadalla; (35) Abu Muawaad; (36) Daghbag; (37) EL Hisinat; (38) Bokari; (39) Umm Samra; (40) Abu Dabbab; (41) Abu Qaria; (42) Umm Saltit; (43) Bezah; (44) Umm Selim; (45) Barramiya; (46) Dungash; (47) Samut; (48) Umm Hugab; (49) Urf EL Fahid; (50) Atud; (51) Sukkari; (52) Umm Tundeba; (53) Hanglaliya; (54) Kurdeman; (55) Sabahia; (56) Umm Ud; (57) Allawi; (58) Lewewi; (59) Dweig; (60) Hamash; (61) Geli; (62) Qulan; (63) Kab EL Rayan; (64) Sheialik; (65) AbuRahaya; (66) Wadi Khashb; (67) Umm Eleiga; (68) Betan; (69) Qurga Rayan; (70) Hutit; (71) Kalib; (72) Kurtunos; (73) EL Hudi; (74) Hariari; (75) Um Shira; (76) Neqib; (77) Haimur; (78) The Nile Valley (Block E); (79) Umm Garaiart; (80) Marahib; (81) Atshani; (82) Murra; (83) Filat; (84) Seiga I; (85) Seiga II; (86) Umm Shashoba; (87) Abu Fass; (88) Umm Tuyur; (89) Betam; (90) Umm Egat; (91) Kurbiai; (92) Romit.

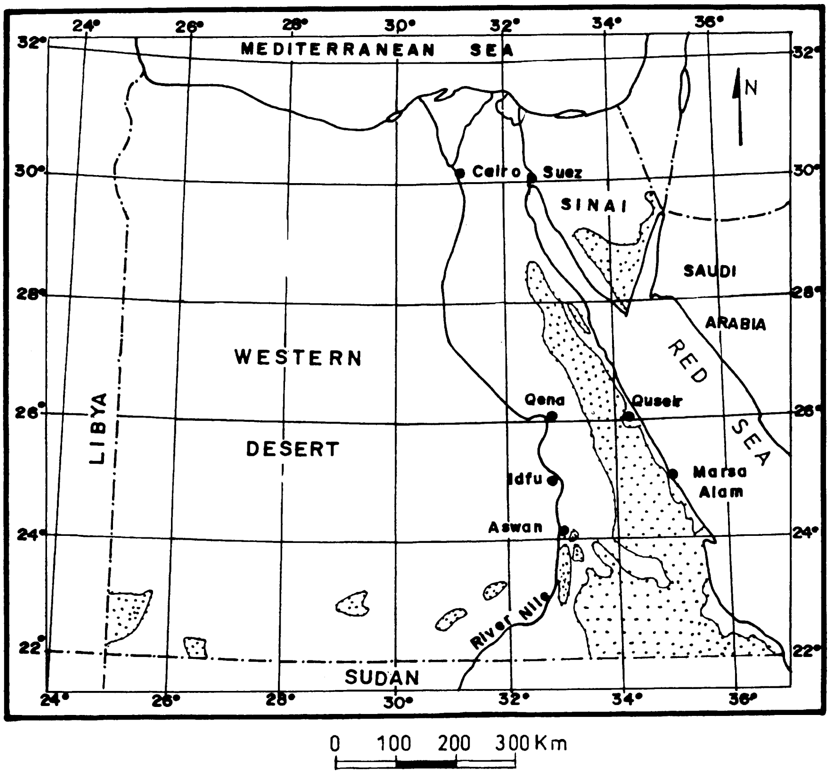

Fig. 2. Distribution of basement outcrops in Egypt. ▭ Younger sedimentary formations, ⁙ Precambrian basement rocks.

ers considered the shield to be evolved as intracratonic ensialic geosyncline with a basement of older sialic material.

With the advent of the concept of plate-tectonics, several plate tectonic models were proposed for the development of the Nubian Shield. These models included: a juxtaposed volcanic arc resulting from opening and closure of a limited basin (Garson and Shalaby, 1976), development of a rift ocean basin and subsequent related phenomena (Church, 1979), episodic and/or successive evolution of ensimatic island arcs which were swept and welded together (Gass, 1977).

The presence of sialic detritus and granitic pebbles in the metasediments of the Egyptian basement rocks stands against the acceptance of the ensimatic island arc model as a working hypothesis for the evolution of the Nubian Shield (Hashad and Hassan, 1979).

In fact, the dispute among the investigators of the Nubian Shield arises primarily from debate about the occurrence of Pre-Panafrican basement rocks within the Nubian Shield. The western edge of the basement exposures, changes west of the Nile into a series of high grade migmatitic gneisses, migmatites and partly granulites with intercalated high grade supracrustal rocks like marbles, calc-silicates and amphibolites (Schandelmeier et al., 1988). There is considerable evidence that these rocks belong to an older sialic continental plate (Abdel Monem and Hurley, 1979; Harris et al., 1984; Bernau et al., 1987). This continental plate was named Nile Craton (Rocci, 1965; referring to the Uweinat inlier) or East Sahara Craton (Kroner, 1979; referring to the area between Hoggar and Arabian–Nubian Shield).

In the light of available radiometric age data, Greiling et al. (1994) suggested that the boundary between East Sahara Craton and the Panafrican belt occurs as a north–south trending line just to the western limit of the basement exposures (Fig. 3). Moreover, El Gaby et al. (1988), from a synthesis of available geological, geochemical and radiometric age data, came to a conclusion that the contintal craton crust extends east-

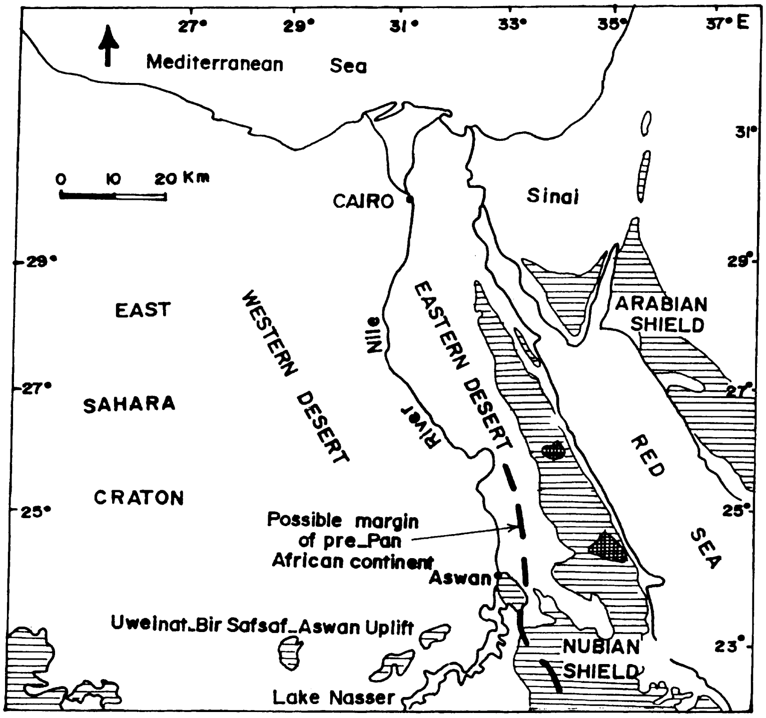

Fig. 3. The possible boundary between the East Sahara Craton and the rocks of the Panafrican belt and the tectonic windows (compiled from El Gaby et al., 1988; Greiling et al., 1994). ▤ Rocks of the Panafrican belt, ▦ Windows.

ward into the Eastern Desert underneath the Panafrican cover and now is exposed in several tectonic windows (e.g., Meatiq and Hafafit).

The presence of continental crust underneath the Panafrican rocks can be indirectly inferred, as El Gaby et al. (1988) mentioned from: (1) the presence of molasse-type sediments, which characterizes the continental margin orogenic belts (Windley, 1984, p. 267), (2) the abundance of granitoid intrusions which do not form by partial melting of subducted oceanic crust or of upper mantle, but originate through interaction of subduction-related magmas with continental crust at depth (Wyllie, 1983).

Generally speaking, there are two major lithological associations in the Eastern Desert (Shackleton et al., 1980; Ries et al., 1983; El Gaby et al., 1988; Al Filali et al., 1993; Neumayr et al., 1996; Mansour et al., 1999). These are: (1) Pre-Panafrican rocks (infrastructure), which comprises gneisses, migmatites and amphibolites and (2) Panafrican assemblage (suprastructure), which comprises ophiolites, island-arc volcanic and volcaniclastic rocks. The latter are metamorphosed to greenschist–amphibolite facies, and are intruded by syn- to late-tectonic calc-alkaline granites.

The boundary between the two major lithological associations is tectonic (Abdel Khalek et al., 1992; Hamimi et al., 1994) and is produced of low angle thrusting (Al Filali et al., 1993; Kroner et al., 1987). Ophiolites are commonly located along the major thrust faults (El Gaby, 1983; El Gaby et al., 1988) and particularly along the decollement surface between the obducted Panafrican belt (suprastructure) and the underlying old continental margin (infrastructure).

El Gaby et al. (1988) believe that the island arc was swept against the old continent, thereby thrusting back-arc ophiolites and the island-arc volcanic and volcaniclastic rocks onto the margins of the old continent. The Panafrican belt then acquired a Cordilleran character.

Depending on the above concepts, the author is inclined to the belief that the Panafrican belt formed in an environment identical to present-day active continental margin orogenic belts. Accordingly, it is here suggested that, the tectonic–magmatic evolution of the belt took place in three stages; namely island-arc stage, orogenic stage and post-orogenic stage. Each stage is characterized by its own specific style of gold mineralization.

2.1. Island-arc stage

The evolution of the Panafrican belt seems to be started some 1000–2000 Ma ago (Gass, 1982) with intra-oceanic island arcs formed as result of subduction between two converging plates of oceanic lithosphere (Gass, 1982; El Gaby et al., 1988; El-Ramly et al., 1998). Volcanic rocks of this stage are equivalent to younger metavolcanics (YMV) of Stern (1981) and Shadli metavolcanics (El Ramly, 1972). They are represented mainly by metabasalts, metabasaltic andesites and metadacites (El-Ramly et al., 1998). The volcaniclastic rocks of this stage, which accumulated in intra-arc basins, include tuffs and volcanogenic wackes that are often banded and graded bedded. The volcaniclastic rocks are frequently intercalated with Banded Iron Formation (BIF) of Algoma-type particularly in the central part of the Eastern Desert and associated further to the south with massive sulphide deposits similar in many respects to the Canadian sulphide deposits (Hussein et al., 1977).

Geochemically, basalts and basaltic andesites show tholeiitic affinity, whereas andesites and dacites show calc-alkaline affinity (Botros, 1991; El-Ramly et al., 1998). The mineral assemblage of these volcanic and volcaniclastic rocks indicates that they are metamorphosed in the greenschist to epidote–amphibolite facies transition (Takla et al., 1997b). The metamorphism was synchronous with the compressional deformation events that happened during the Pan-African orogeny (El Gaby et al., 1988; El-Ramly et al., 1998).

Ophiolites were formed in back-arc basins during this stage in the Upper Proterozoic (Stern, 1981; Akkad et al., 1996). A typical ophiolitic succession has been recognized in Wadi Ghadir (El Sharkawy and El bayoumi, 1979). These ultramafic rocks have been metamorphosed (El Gaby et al. 1988) to serpentinites during submarine metamorphism. Ophiolitic serpentinites occur in the Panafrican belt as fragments embedded in a volcano–sedimentary matrix. These fragments have variable dimensions from pebble size to mountaineous ranges (Takla and Suror, 1996).

2.2. Orogenic stage

During the orogenic stage, ophiolites and island arc volcanic and volcaniclastic rocks were thrust in a NNW trend (Shackleton et al., 1980; Ries et al., 1983; Habib et al., 1985) over the pre-Panafrican continental margin (El Gaby et al., 1988). Akkad et al. (1996) believe that collision of arc–arc and/or arc–continent has resulted in disruption of the oceanic lithosphere underlying both the island arc and adjacent back-arc basins. This event was followed by emplacement of the disrupted oceanic lithosphere in the form of dismembered ophiolitic components. These features characterized the orogenic stage or tectogenesis (El Gaby et al., 1988). The subduction was active under the continent while the process of overthrusting was operative along the thrust planes. A pronounced phase of calc-alkaline magmatic activity, represented by the emplacement of G-1 and G-2 granites (Hussein et al., 1982) and the eruption of their volcanic equivalents (Dokhan volcanics) took place (El Gaby et al., 1988). According to Hussein et al. (1982), G-1 granites are subduction-related I-type magnetite-series granites, formed in old Benioff zones by partial fusion of the mantle wedge with little of no crustal melt contribution. G-2 granites, on the other hand, are suture-related granites formed in the thickened crust due to folding and thrusting. They are characterized by being S-type, ilmenite series granites.

At the orogenic stage or slightly later, coarse terrigenous molass-type sediments (Hammamat sediments) were deposited in a non-marine intermontane basins (Grothaus et al., 1979). These basins have different tectonic settings, and the basin evolution is controlled by the position of the basin within the orogen (Messner, 1996).

A suite of intrusive ultrabasic and basic rocks was intruded contemporaneously with the calc-alkaline magmatic rocks (El Gaby et al., 1988). These rocks occur as small, frequently layered intrusions and sills. They represent continental margins magmatism that followed molass-type sediments, but older than G-2 granites (Takla and Hussein, 1995).

The compressional deformation event that characterized the orogenic stage was also synchronous with the regional metamorphism to greenschist–amphibolite facies. Obducted Panafrican ophiolites and island arc volcanic and volcaniclastic rocks were metamorphosed to talc carbonates and actinolite schist, respectively (El Gaby et al., 1988). Extensional shear fractures reflected in brittle–ductile shear zones were broadly contemporaneous with the intense compressional tectonic regime. These fractures opened spaces in which mineralizing fluids penetrated (Loizenbauer and Neumayr, 1996).

During the orogenic stage, the infrastructural rocks were highly affected by the Panafrican thermal event. A dynamic metamorphism is evidenced along the decollement surface between the Panafrican supracrustal rocks and the infrastructure, leading to the formation of mylonites. At deeper levels, on the other hand, the infrastructures were subjected to migmatisation and granitization (El Gaby et al., 1988, 1990) leading to and concomitant with the development of G-1 granites. Gold belts of the vein-type mineralization coincide with these centers of calc-alkaline magmatic activity (El Gaby, 1983). Fig. 4 shows the essential elements of the orogenic stage.

2.3. Post-orogenic stage

By the end of Panafrican orogeny, about 570 Ma ago, until the Tertiary, the basement was intermittently intruded by a number of subalkaline to peralkaline A-type granite bodies (El Gaby et al., 1988). These post-kinematic silicic rocks are lumped together as G-3 granites (Hussein et al., 1982). By definition, G-3 granites are intra-plate anorogenic subalkaline to peralkaline granites formed within the plates subsequent to cratonization. They are related to hot spots and incipient rifting. G-3 granites host Mo, Sn, W, Nb–Ta and U mineralization in the Eastern Desert of Egypt.

3. Gold deposits in the Eastern Desert of Egypt

In the following, the different styles of gold mineralization in the Eastern Desert of Egypt are classified with respect to their tectonic environment.

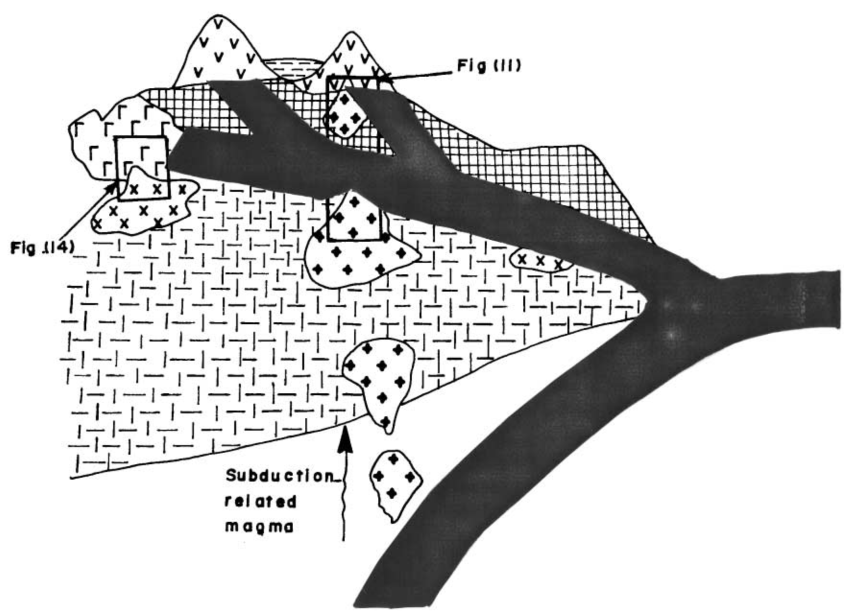

Fig. 4. Sketch diagram illustrating both obduction of ophiolites and island-arc volcanic and volcaniclastic rocks onto the old content and subduction of oceanic crust under continent during the orogenic stage. Molasse-type sediments (Hammamat sediments), Dokhan volcanics, Younger gabbro, Subduction-related granites (G-1 granites), Suture-related granites (G-2 granites), Island-arc volcanic and volcaniclastic rocks, Old continent, Oceanic crust.

3.1. Gold mineralization accompanying the island-arc stage

Gold mineralization associated with the island-arc stage is represented by gold hosted in Algoma-type BIF and associated tuffaceous metasedimentary rocks, and gold hosted in volcanogenic massive sulphide deposits (Fig. 5).

3.1.1. Gold hosted in Algoma-type BIF

The deposits of BIF in the Eastern Desert occur as sporadic deposits in layered volcanic and volcaniclastic rocks of the island arc stage. They are localized in the central parts of the Eastern Desert with the exception of two occurrences at Semna and Abu Marawat further north (Fig. 6). At present, it is well established that BIF in the Eastern Desert resembles those found in Archaean and younger volcanic assemblages and belongs to the class of Algoma-type deposits which are related in time and space to volcanic activity (Sims and James, 1984; Botros, 1995a; Aly et al., 1992; Takla et al., 1995b).

The majority of BIF in the Eastern Desert belong to the oxide facies where the iron minerals are represented by hematite and magnetite. However, carbonate and sulphide facies are also encountered in some localities (Aly et al., 1992; El Gaby et al., 1994).

Recently, gold mineralization associated with oxide facies of BIF at Abu Marawat gold prospect was studied (Botros, 1991). At this locality, BIF is located in the upper parts of Gabal (mountain) Abe Marawat (Fig. 7) which rises up to 948 m above sea level. BIF occurs as sharply defined horizon within volcanic–sedimentary succession. Volcanic rocks are dominated by pillowed basalts (Fig. 8) that were formed during the early stages of arc development (immature island arc) (Botros, 1991). Sedimentary rocks at Abu Marawat gold prospect are represented by graywacke, laminated and pebbly mudstone and polymict conglomerate. The volcano–sedimentary succession is regionally metamorphosed into greenschist facies.

Gold occurs up to 2.15 ppm in the formation (Table 1) either enclosed in the flaky hematite crystals of the hematite mesoband (Fig. 9) and/or as fine inclusions in the gangue constituents of the magnetite mesoband (Fig. 10).

BIF in the Eastern Desert of Egypt satisfies the initial criteria for syngenesis in that it is stratiform and confined to particular lithologies (layered volcaniclastic rocks and intercalated lava flows). Other criteria are: (1) the constituent minerals participated in all deformation and metamorphic events recorded in the adjacent rocks. They are metamorphosed to greenschist facies, with the development of chlorite, sericite and the iron silicate stilpnomelane; (2) mineralization is not restricted to specific folds or fault structures or zones of fracturing; (3) wall–rock alterations are not recorded.

The genesis of these deposits summarized by Sims and James (1984) is accepted here. They state that these deposits originated as chemical sediments of exhalative fumarolic source in a number of separate small basins developed between intraoceanic island arcs. BIF was accumulated with volcaniclastic tuffs and intercalated lava flows in shallow submarine environments during periods of quiescence in submarine volcanic activity.

On the other hand, the genesis of the auriferous BIF at Abu Marawat gold prospect was attributed to interaction between volcanically derived fluids (hot brines) and sea water (Botros, 1991). The hot brines were capable of leaching iron, silica, gold and other associated elements from basaltic andesites and basalts of tholeiitic affinity that characterized the early stage of the island-arc volcanicity (immature arc). When these brines mixed with seawater, auriferous BIF was deposited as chemical sediments (Botros, 1991). After diagenesis and lithification, they were folded more than once, faulted and regionally metamorphosed into greenschist facies.

3.1.2. Gold hosted in tuffaceous metasedimentary rocks (exhalites)

Metatuffaceous sedimentary rocks, which are often banded, graded bedded and intercalated with BIF, are usually gold bearing (Botros, 1993). This style of mineralization is localized in the outcrops were both volcanic and volcaniclastic rocks are intimately intercalated with each other. The author believes that this style of gold mineralization in the Eastern Desert of Egypt may represent a break or termination within the volcanic stratigraphy, and in areas occupied by island arc volcanic and volcaniclastic rocks, such break is confirmed by the occurrence of BIF which is also considered as chemical sediments precipitated during breaks of volcanic activity (Sims and James, 1984).

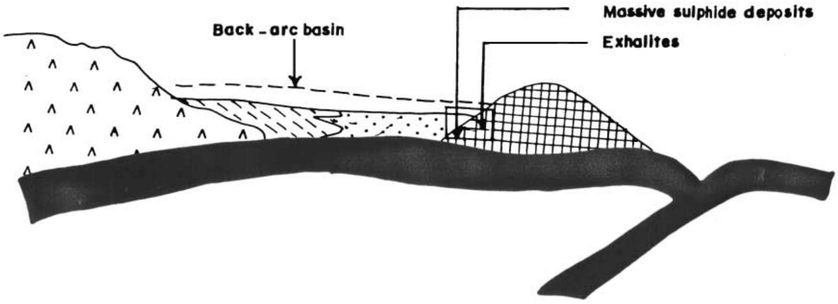

Fig. 5. Sketch showing the island-arc stage and accompanying gold mineralization. Island-arc volcanic rocks, Volcaniclastic rocks, Shelf sediments, Old continent, Oceanic crust.

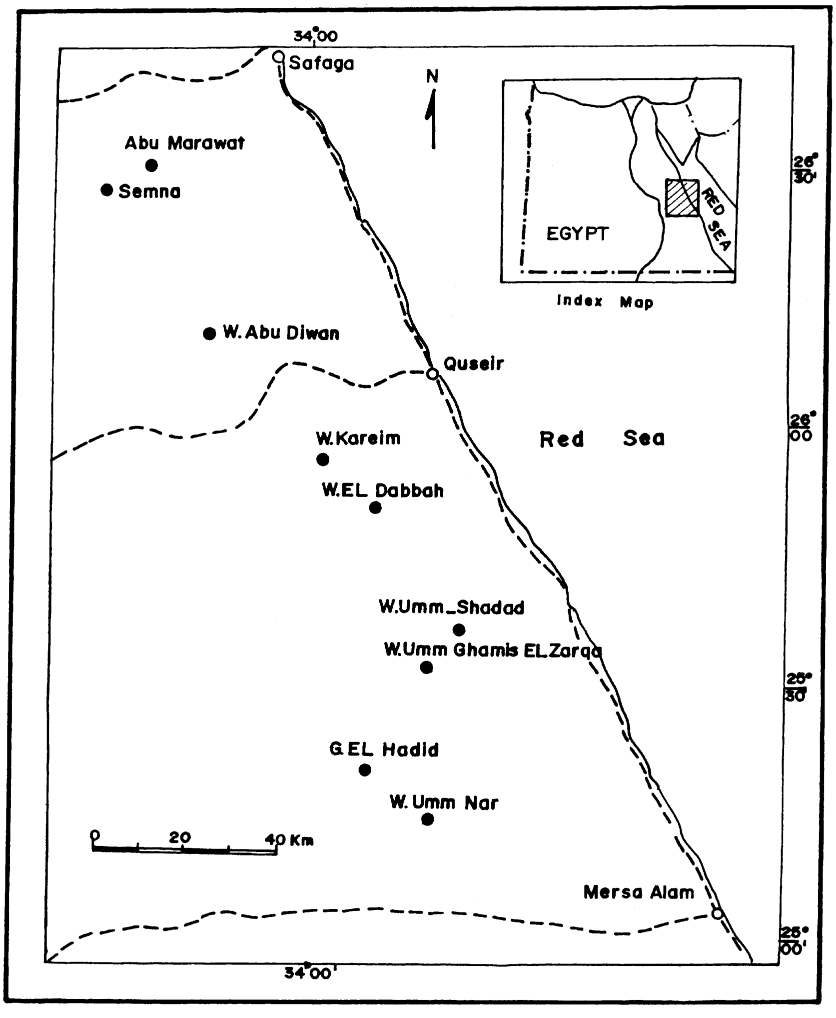

Fig. 6. Distribution of major iron deposits in Egypt (modified after Sims and James, 1984). Asphaltic roads, Coastal city.

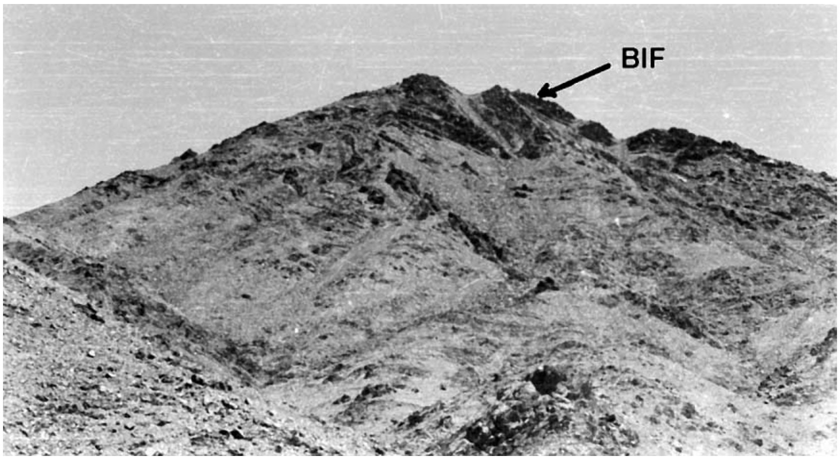

Fig. 7. Algoma-type Banded Iron Formation (BIF) occurring as sharply defined stratigraphic unit within Panafrican layered basaltic andesites, basalts, tuffs and volcanogenic wackes, Abu Marawat area, Eastern Desert of Egypt.

The anomalous gold in the auriferous tuffaceous sediments (up to 11.62 ppm in Abu Marawat area; Botros, 1991) can be considered as a type of exhalative deposits analogous to present-day hot springs or fumarolic discharges. References to this phenomenon has been made by Viljoen et al. (1969), Viljoen (1984), Bavinton and Keays (1978) and Saager et al. (1982).

3.1.3. Gold hosted in volcanogenic massive sulphide deposits

In the Eastern Desert within the belt of island arc volcanics and volcaniclastic rocks, a number of generally small massive sulphide deposits are distributed (Hussein, 1990). The volcanogenic massive sulphide deposits are integral part of, and coeval with, the volcanic complex in which they occur (Searle et al., 1976).

Most studies on massive sulphide deposits in Egypt are concentrated mainly on Umm Samiuki deposit being the largest in reserves and the best in ore grade. For that area, Searle et al. (1976) divided Shadli volcanic rocks (island–arc volcanics) into the older Wadi Umm Samiuki volcanic rocks and a younger Hamamid assemblage (Table 2). The Wadi

Fig. 8. Close view of pillowed metabasalts at Abu Marawat area, Eastern Desert, Egypt.

Table 1
Gold and trace element contents (ppm) of Algoma-type Banded Iron Formation from Abu Marawat area, Eastern Desert, Egypt

Au	Cr	Ni	Co	V	Zn	Cu	Pb	Ba
1.71	30	12	4	185	110	3	85	130
1.65	36	19	5	121	79	6	71	127
2.00	28	10	4	160	83	5	73	133
1.71	38	13	8	135	92	7	100	153
2.05	25	9	7	169	89	4	88	161
1.37	33	12	6	170	77	8	91	141
1.46	37	15	9	118	116	9	85	95
0.80	41	17	3	140	128	4	87	107
1.00	28	11	6	138	108	6	89	125
1.83	27	14	5	145	122	3	70	118
2.15	40	9	7	157	77	8	83	132
1.88	39	13	8	126	93	5	62	100
1.21	31	11	5	119	70	4	93	149
0.77	43	17	4	110	88	3	110	103
1.75	27	12	5	182	100	8	65	138
1.09	25	20	7	130	67	3	71	146
1.44	31	10	6	137	75	4	96	110

Data from Botros (unpublished data).

Umm Samiuki volcanics are a thick succession of submarine cyclic basic and acid volcanics with minor intercalated-banded tuffs and chert beds. The Abu Hamamid group includes two distinct cycles of volcanism. Each cycle starts with pillowed basalt and terminates with thick beds of rhyolitic volcaniclastic rocks. Vent complexes are recorded in the area and are thought to be the centers of eruption for the acidic phase of the first cycle. The massive sulphide body is confined to the acid coarse pyroclastics of the first cycle of Abu Hamamid group (Searle et al., 1976). The body occurs along a specific stratigraphic horizon, namely that separating the brecciated rhyolite and vent facies on one hand, and the banded graded bedded tuffs on the other hand. The upper contacts of the massive sulphide body are sharp and well defined, while on the footwall side, an extensive pipe or funnel of alteration is present. Here, the alteration zone beneath the ore body at Umm Samiuki area is characterized by septechlorite and talc, associated with variable amounts of carbonates and tremolite (Rasmay et al., 1983). The talc thus formed in the keel zone is now being exploited economically at Darhib talc mine (Hussein, 1990).

The ore lenses are banded with local development of sedimentary textures. Moreover, they show some zonation whereby Zn increases towards the hanging wall, while Cu increases towards the footwall (Hussein, 1990).

These deposits are similar in many respects to those described from Canada (Hussein et al., 1977; Hussein, 1990). The points of similarities are: (1) both are associated with calc-alkaline, submarine volcanic activity; (2) both show strong spatial association with fragmental pyroclastics of rhyolitic composition; (3) both consist of two main types of ore, massive sulphides and stringer ore; (4) both show compositional zoning; (5) both are underlain by foot wall rock alterations (keel zone) that are dominated by chlorite, carbonate and talc.

Gold occurs in both the massive sulphide body and the keel zone. The values of gold recorded in the keel zone at Darhib, Abu Gurdi, and Um Selimat are relatively high if compared with the analyzed samples in the massive sulphide body of Umm Samiuki (Table 3). For the latter, gold values are extremely low (<0.3 ppm) as would be expected in such mineralogical environment with little pyrite (Searle et al., 1976). Sulphides associated with gold in Umm Samiuki massive sulphide body are represented mainly by sphalerite, chalcopyrite, pyrite and galena in decreasing order of abundance (Helmy and Shalaby, 1999). On the other hand, ore minerals associated with gold in the keel zone at Darhib and Abu Gurdi are represented mainly by chalcopyrite, pyrite, sphalerite and galena in decreasing order of abundance (Helmy and Shalaby, 1999). It is clear that gold is associated with chalcopyrite and it seems that ascending hydrothermal fluids precipitated gold and copper before reaching the sea floor.

The lack of fluid inclusion studies render it impossible to determine exactly the nature of the mineralizing fluid. It is here assumed that gold and copper were deposited in the keel zone by high temperature, low pH fluids that carried gold and copper as chloride complexes. Deposition took place due to decreasing of temperature and/or increasing pH (Hannington and Scott, 1989).

Our belief that gold grades increase along with copper in the lower parts of the massive sulphide body is in harmony with results obtained from the western mine of Umm Samiuki area (Searle et al., 1976, pp. 29).

The geological environment of both auriferous BIF and associated tuffaceous sediments on one hand, and massive sulphide deposits, on the other hand, suggests

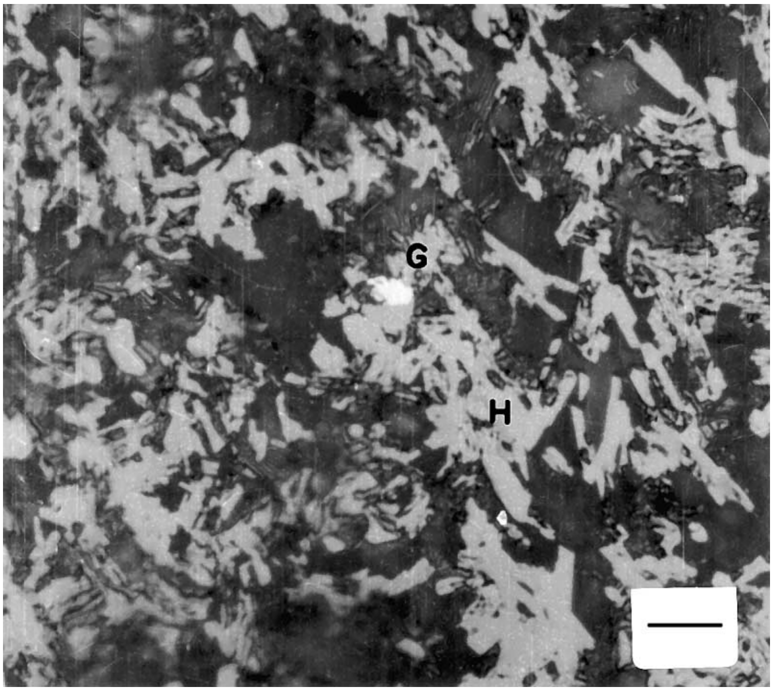

Fig. 9. Photomicrograph of Algoma-type BIF showing minute gold speck (G) enclosed in the hematite flake (H). Abu Marawat area, Eastern Desert, Egypt. R.L., bar length represents 0.02 mm. (from Botros, 1991).

that they formed in the same environment, i.e., submarine volcanism during the island-arc stage. BIF of the central Eastern Desert was formed during the early stages of island arc formation (immature arc), whereas the mature island-arc stage was accompanied by the formation of volcanogenic massive deposits such as those of Umm Samiuki (Hussein, 1990).

Geological, mineralogical and geochemical characteristics of gold deposits formed during the island-arc stage in the Eastern Desert of Egypt are analogous

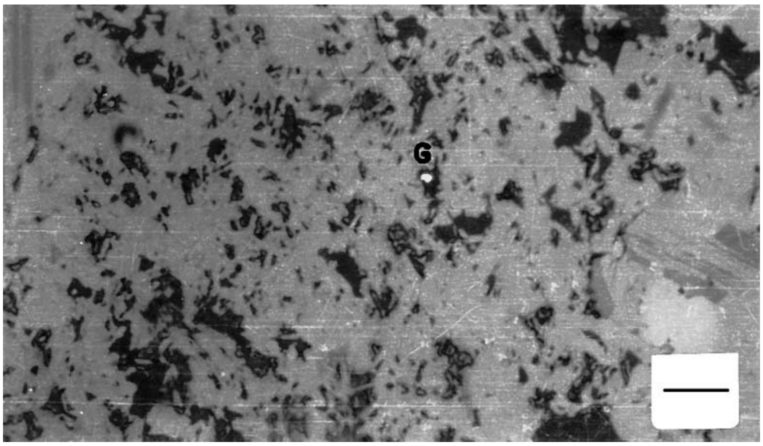

Fig. 10. Photomicrograph of Algoma-type (BIF) showing minute gold speck (G) enclosed in the gangue minerals, Abu Marawat gold prospect, Eastern Desert of Egypt. Bar length represents 0.02 mm. (from Botros, 1991).

Table 2
Stratigraphical succession of the Shadli volcanic rocks (island-arc volcanic rocks) in Um Samiuki area, Eastern Desert, Egypt (after Searle et al., 1976)

Shadli Volcanic rocks	
Cycle 2	
	Dolerite
Hammid Assemblage	Upper banded tuffs and cherts
	Volcanic breccias
Acid-lava phase	Dacite and related intrusions
	Volcanic breccias and turbidites
Basic lava phase	Upper pillow lavas and hyaloclastic
	Basic vent breccias and lava
	Lower banded tuffs and cherts
Cycle 1	
Acid–lava phase	Acid vent rocks and mineralization
Basic–lava phase	Micro-diorite
	Lower pillow lavas
Wadi Umm Samiuki volcanic rocks	Basic and intermediate lavas with rhyolites and acid Volcaniclastic rocks

Data from Searle et al. (1976).

to those suggested by Hutchinson (1987) for Late Proterozoic gold deposits. The points of similarities are: (1) occurrence in volcano–sedimentary succession; (2) presence of stratiform auriferous exhalites such as BIF and massive base metal sulphide deposits; (3) dominance of pillowed, variolitic, tholeiitic basalts; (4) proximity to facies-transitional contacts between the volcanic and sedimentary units.

3.2. Gold mineralization accompanying the orogenic stage

Gold mineralization associated with the orogenic stage is represented by vein-type mineralization (main target of gold mineralization in Egypt) hosted in different lithologies and gold mineralization along the sheared contacts of the ophiolitic serpentinites. Gold mineralization associated with porphyry–copper mineralization and quartz veins at the contacts of younger gabbros and G-2 granites also characterize this stage.

3.2.1. Vein-type mineralization in the Eastern Desert

In the present work, it is believed that vein-type gold deposits of the Eastern Desert have been formed during the orogenic stage synchronous with regional metamorphism (greenschist to amphibolite-facies) and attendant upon calc-alkaline I-type granites (G1 granites of Hussein et al., 1982).

Vein-type mineralization of this stage is encountered mainly in the metamorphic rocks and/or the granitic rocks surrounding them (Botros, 1995b). It seems that metamorphic grade is important because most auriferous quartz veins are hosted in rocks which have been metamorphosed at conditions below the amphibolite–greenschist boundary (Botros, 1995b). These T–P conditions were suitable for the formation of brittle–ductile structures that host these veins. It is well established that brittle–ductile deformation is characterized by fluctuating fluid pressures, multiple fracturing and channeling of fluid along a fracture zone (Kerrich, 1986). This results in high fluid to rock ratios along these channel ways (Sibson et al., 1975; Ramsay, 1980; Vearncombe et al., 1989) and in turn ideal conditions for gold mineralization (Fig. 11).

Host rocks, lode type, alteration assemblage and ore minerals of the vein-type mineralization in some localities of the Eastern Desert (Table 4) were investigated by some workers (Kochine and Basyuni, 1968; Sabet and Bordonosov, 1984; Osman, 1989; Osman and Dardir, 1989; Botros, 1991; Takla et al., 1990, 1995a; Hussein, 1990; Elshimi, 1996; Shazly et al., 1998).

Quartz veins are structurally controlled, being fissure fillings, confined to fault planes, or zones of intensive fracturing (Hussein, 1990). They may be arranged as a series of en echelon veins with pinches and swells. The main veins are always accompanied by parallel veinlets and stringers to form ore zone of considerable thickness as compared to the veins. At Barramiya, Atud, Hangaliya, Umm Rus and Sukari,

Table 3
Gold, copper, zinc and lead contents of massive sulphide and keel zone, Eastern Desert, Egypt

Area	Cu% average	Zn% average	Pb% average	Au ppm	Remarks
Umm Samiuki	2.19	21.66	0.50	> 0.22	Massive sulphide body
Abu Gurdi	3.20	4.79	0.41	1.2–2.7	Keel zone
Darhib	3.50	7.50	0.30	0.6–2.1	Keel zone
Um Selimat	3.87	0.40	0.25	0.52–4.06	Keel zone

Data from Abdel Salam et al. (2000), Searle et al. (1976).

Table 4
Characteristic features of some important vein-type gold deposits in the Panafrican belt, Eastern Desert, Egypt

Deposit	Host rocks	Lode type	Alteration assemblage	Ore minerals
Hangalia	Granite	Shear zone vein arrays	Ser-K	g + py + cpy ± tet ± sl ± gn ± apy
Sukkari	Granodiorite; schist	Shear zone vein arrays	Ber-List	g + py + apy ± sl ± cpy ± gn
Samut	Granodiorite; schist; mafic volcanics	Quartz veins enclosed in shear zones of pinch and swell structure	Ep-Ch-List	g + py + apy + cpy
Hamash	Granite; diorite	Shear-zone vein arrays	Ep-Ch	g + py
El-Eradia	Tonalite–granodiorite association	Shear-zone vein arrays	Q-Ser-Ch-Carb-Hm	G + py
Dungash	Metavolcanic and metapyroclastic Rocks	Shear-zone vein arrays	Ser-Carb-List	g + py + apy ± cpy ± po ± sl ± gers
Haimur	Metabasalt; schist	Quartz veins enclosed in brittle–ductile shear zone	Ser-Q-Carb	g + py + cpy
Umm Garaiart	Metaandestic tuffs	Steeply dipping veins	Ser-Q-Carb	g + py + cpy
Marahib	Metaandesite	Quartz veins in brittle–ductile shear zone	Q-Carb	g + py
Hariari	Diorite	Quartz veins in brittle–ductile shear zone	Ser-Carb	g + py

Data from Arslan et al. (2000), Helmy (2000), Helmy and Kaindl (1997), Hussein (1990), Elshimi (1996), Khalil et al. (2000), Kochine and Basyuni (1968), Osman (1989), Osman and Dardir (1989), and Sabet and Bordonosov (1984).
Abbreviations: Q—quartz, Carb—carbonate, Ch—chlorite, Ep—epidote, Ser—seircite, Ber—bersite, List—Listawenite, Hm—hematite, apy—arsenopyrite, cpy—chalcopyrite, gers—gersdorffite, gn—galena, po—pyrrhotite, py—pyrite, sl—sphalerite, tet—etrahedite, g—gold.

this zone ranges between 15 and 20 m in thickness and reaches up to 100 m at El-Sid gold mine. Along the strike, the ore zones extend for some hundreds of meters and may continue for considerable distance along the dip, for example, 455 m at El Sid. The main veins vary in width, generally between 0.6 and 1.5 m, but may reach up to 5 m as at Semma, Sukari and Umm Egat (Hussein, 1990).

The mineralized veins consist dominantly of quartz and carbonates, with subordinate amounts of sulphide minerals. Pyrite is the dominant sulphide mineral, commonly accompanied by minor chalcopyrite and arsenopyrite and one or more of sphalerite, tetrahrdrite, galena, pyrrhotite and gersodorffite. The sulphide minerals occur as disseminations and fracture fillings in the quartz. Some deposits, such as Hamash, exhibit an appreciable increase of copper minerals (Osman, 1989).

The gold content of the mineralized veins varies considerably even in the same vein. It may reach a maximum of 467–1203 ppm as in Atud and Atalla deposits. However, the average does not usually exceed 11–30 ppm (El-Ramly et al., 1970 and references therein).

Native gold occurs in most cases as minute specks and discrete scattered flakes within the quartz vein or as small inclusions in sulphides particularly pyrite and arsenopyrite (Shazly et al., 1998). SEM analyses show that gold may carry some amounts of silver up to 34.49 wt.% (Shazly et al., 1998). The ratio of silver to gold in the veins varies from 1:2 to 1:17 (Hume, 1937).

The mineralized veins are surrounded by hydrothermal alterations that extend for 1–2 m on both sides of the vein. The most important types of wall rock alterations are sericitization, beresitization, silicification, sulphidation, carbonatization, listwaenitization, chloritization and kaolinitization (Botros, 1993). The alteration zones around the mineralized veins are of economic interest as they contain reasonably high gold values (Botros, 1993) (Fig. 12).

A number of fluid inclusion studies in vein-type gold deposits in the Panafrican belt are available (Harraz et al., 1992; El Kazzaz, 1996; Loizenbauer and Neumayr, 1996; Shazly et al., 1998). Some of the results from these studies are summarized (Table 5).

It is clear that the auriferous fluids are characterized by: (1) ubiquitous content of CO_2 in the inclu-

Table 5
Summary of fluid inclusion microthermometric data for vein-type gold deposits from the Eastern Desert, Egypt

Deposit or area (Reference)	Fluid inclusion data
El Sid-gold deposit (Harraz et al., 1992)	Size: 10–20 μm Genetic class: primary and pseudoprimary Shape: rounded shapes Types of inclusions: liquid-rich, vapour-rich Salinity: 10.2–19.4 equiv. wt.% NaCl CO_2: 29–62 mol% Homogenization Temp.: 241–405 °C
El Sid-gold deposit (Loizenbauer and Neumayr, 1996)	Size: 5–50 μm Genetic class: secondary and pseudosecondary Shape: slightly rounded to irregular shapes Types of inclusions: liquid-rich, vapour-rich, and mixed CO_2–H_2O fluid Salinity: 5 equiv. wt.% NaCl CO_2: 65–75 mol% Homogenization Temp.: 300–350 °C Trapping pressure: 1.8–2.3 kbars
Atshani old gold workings (El Kazzaz, 1996)	Size: < 15 μm Genetic class: primary and secondary Shape: oblate, cylindrical, and irregular forms Types of inclusions: liquid-rich, vapour-rich Salinity: 25 equiv. wt.% NaCl CO_2: ubiquitous content Homogenization Temp.: 280–320 °C Trapping pressure: 2 kbars
Umm Samra area (Shazly et al., 1998)	Size: 5–25 μm Genetic class: primary and secondary Shape: isolated and regular shapes Types of inclusions: liquid-rich, vapour-rich Salinity: 0.7–3 equiv. wt.% NaCl CO_2: 30–50 mol% Homogenization Temp.: 246–310 °C Trapping pressure: 0.75–0.85 kbars
Umm Baraka area (Shazly et al., 1998)	Size: 6–20 μm Genetic class: primary and secondary Shape: regular, equant form Types of inclusions: liquid-rich, vapor-rich Salinity: 0.7–8.9 equiv. wt.% NaCl CO_2: 25–75 mol% Homogenization Temp.: 235–353 °C Trapping pressure: 0.65–0.98 kbars

sions (29–62 mol% CO_2); (2) wide range of salinity (0.7–19.4 equivalent wt.% NaCl); and (3) wide range of temperatures of homogenization of the primary inclusions (235–450 °C) with a concentration of results in the 235–353 °C.

Through observations of many gold deposits in the world, a general consensus exists that mineralizing fluids of metamorphic origin are H_2O–CO_2 rich, low salinity (commonly less than 6 equivalent wt% of Nacl) fluids (Foster, 1989; Groves et al., 1989; Peters and Golding, 1989; Goldfarb et al., 1989). Comparing the ideal metamorphic fluids with our available data, it becomes clear that these data do not suggest a unique origin for the fluids that leached gold from source rocks.

Isotopic analyses of oxygen and hydrogen were performed on separated quartz and calcite minerals from El Sid gold mine (Harraz et al., 1992). The $\delta^{18}O$ values of the quartz samples range from 10.63 to 14.50 per mil, while δO values of calcite samples range from 8.2 to 18.80 per mil. On the other hand, δD values of quartz range from − 127 to − 81 per mil, while δD values of calcite range from − 105 to − 42 per mil.

It is apparent that both oxygen and hydrogen isotopic data show a rather wide range of values which overlap the range of metamorphic and magmatic fluids. Harraz et al. (1992) attributed such discripancy to progressive mixing between meteoric and magmatic-metamorphic waters.

Another oxygen and hydrogen isotopic study was carried out on quartz samples from quartz veins from Atshani old gold workings (El Kazzaz, 1996). The

$\delta^{18}O$ values range from 7.8 to 15.6 per mil, whereas δD values range from -89 to -71 per mil. On the diagram of Taylor (1974), the data plots overlap the fields of metamorphic and magmatic waters (El Kazzaz, 1996).

In the light of the available fluid inclusion, and oxygen–hydrogen isotopic studies. It is here suggested that parent fluids were mainly of metamorphic origin, and the relatively observed high salinity in some fluid inclusion studies could be attributed to mixing of these metamorphic fluids with magmatic fluids and/or modification of parent metamorphic fluids into relatively more saline fluids through fluid-rock interaction.

The metamorphic component of the mineralizing fluids involves generation of H_2O–CO_2 rich fluids during the regional metamorphism of the obducted Panafrican ophiolites and island arc volcanics and volcaniclastic rocks and attendant upon the I-type granites. The H_2O–CO_2 rich fluids are continuously released within the greenschist facies and at the greenschist-amphibolite facies transition which takes place at 450–500 °C (Kerrich and Fyfe, 1988) and is accompanied with large release of volatiles (Goldfarb et al., 1989).

During their passage, the metamorphic fluids, mix with the ascending magmas generated during the Panafrican event (mainly G1 granites of Hussein et al., 1982). The mixed metamorphic-magmatic fluids react with enormous masses of rocks during their passage resulting in their alteration and leaching of gold. According to this concept, gold from various sources would be leached by these mixed metamorphic–magmatic fluids and moves down a temperature gradient away from the amphibolite–greenschist transition at depth to a lower temperature regime in the upper levels where it is deposited in brittle–ductile structures.

The ultimate source of the gold leached by the mixed metamorphic–magmatic fluids is an important factor. The author is inclined to the belief that gold could be derived from various lithologies and until now, no one has clearly identified a volumentrically significant group of rocks of sufficiently high gold content to be identified as source rocks (Keays, 1984). However, the absolute gold content in any lithology appears not to be the critical factor in determining whether this lithology is potential source rock (Viljoen, 1984) but that the mineralogical siting of gold (i.e. accessible to leaching or not) would seem to be the most important parameter (Anhaeusser et al., 1975; Keays and Scott, 1976; Keays, 1984; Viljoen, 1984).

In this paper, one or more of the following rocks can be considered as possible sources for gold.

1. Derivation or leaching of available gold from metabasalts and metabasaltic andesites connected with island–arc volcanic activity (Botros, 1991, 1995b).
2. Derivation of gold from sulphide–facies Algoma-type BIF and auriferous tuffaceous sediments (Botros, 1993).
3. Derivation of gold from the massive sulphide deposits connected with the sub-marine volcanic activity (Botros, 1993).
4. Derivation of gold from Cu–Ni–Co–sulphide mineralization linked with the ophiolitic sequence and which carried gold up to 16.17 g/ton (Garson and Shalaby, 1976).
5. Derivation of gold from the ophiolitic serpentinites (Dardir and Elchimi, 1992; Takla and Suror, 1996).
6. Derivation of gold from the ascending magma generated during the Panafrican event. This is indicated by the presence of Mo, Sn in some auriferous quartz veins (El-Ramly et al., 1970; Botros, 1991).

(Fig. 11) summarizes the formation of vein-type gold mineralization during the orogenic stage.

The model adopted in this paper for the formation of auriferous quartz veins connected with the orogenic stage explains why the majority of vein-type mineralization is confined either to the intrusive masses of granodiorites and diorites (i.e., G-1 granites) or to schists (after volcanic and volcaniclastic rocks) in the close vicinity of these masses (El-Ramly et al., 1970). It is noted that formation of auriferous quartz veins in the granitic rocks itself (i.e., G-1 granites) is explained by the brittle deformation of the granitic rocks. On the other hand, the contrasts in competency between adjacent lithologies (e.g., granitic rocks with brittle deformational characteristics and the surrounding country rocks with a ductile response to stress) can lead to a generation of extensive fracture pattern within the more competent

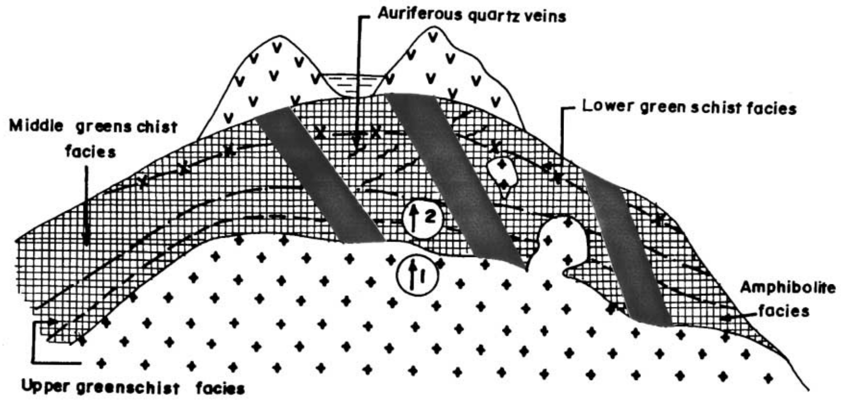

Fig. 11. Sketch diagram showing leaching of available gold from source rocks by mixed metamorphic–magmatic fluids and formation of vein-type gold mineralization. Molasse-type sediments (Hammamat sediments), Dokhan volcanics, Calc-alkaline granites, Island-arc volcanic and volcaniclastic rocks, Dismembered ophiolites, ↑¦ (2) Metamorphically derived fluids, (1) Magmatically derived fluids, Boundaries of facies of metamorphism.

unit, i.e., the granitic rocks. The model also may explain why the North Eastern Desert is completely devoid of veint-type gold mineralization. This is due to the absence of island arc volcanic and volcaniclastic rocks and any member of the ophiolites (possible source rocks for gold), which were eroded completely in such way that deeper crustal levels of the infrastructure are exposed (El Gaby et al., 1983). The model also explains less abundant vein-type gold mineralization in Dokhan volcanics and Hamammat sediments that are not metamorphosed to the facies that could generate a brittle-ductile shears that host most of the auriferous quartz veins in the Eastern Desert.

3.2.2. Gold mineralization along the sheared contacts of the ophiolitic serpentinites

This is another type of mineralization connected with the orogenic stage, in which linear zones of ophiolitic serpentinites show extreme alterations along

Table 6
Characteristic features of some important gold deposits hosted in sheared, linear zones of altered ultramafic rocks, Eastern Desert, Egypt

Deposit	Host rock	Lode type	Trend of quartz veins	Alteration assemblage	Ore minerals
Hutite	Sheared serpentinite traversed by a series of dykes	Brecciated quartz vein	NW–SE, NE–SW	Q-Carb	g + gn
EL Sid	Sheared serpentinite intruded by granite	Quartz veins in extensional joint system cutting across the granite–serpentinite contact	E–W	Car-T	g + py + apy + sl + gn
Barramiya	Graphitic and calcareous schists associated with serpentinite. Quartz-diorite dikes (20 m thick) were reported from the underground workings	Steeply dipping veins; parallel veinlets and stringers; lenticular veins arranged en echelon	E–W (main) N–S, NE–SW, NNE–SSW	Car-T	g + py + cpy

Data from Hussein (1990), Loizenbauer and Neumayr (1996), and Takla et al. (1995a).
Abbreviations: Q — quartz, Carb — carbonate, T — talc, Apy — arsenopyrite, cpy — chalcopyrite, gn — galena, py — pyrite, sl — sphalerite, g — gold.

thrusts and shear zones with the development of a range of talc, talc-carbonate and quartz-carbonate rocks (listwaenites). The latter is frequently mineralized with gold. Examples in the Eastern Desert include Barramiya, El Sid, and Hutite (Table 6).

As previously mentioned ophiolites in the Panafrican belt represent a piece of Upper Proterozoic oceanic crust which first evolved in a back-arc environment. Serpentinization was completed under submarine conditions (Ghoneim et al., 1986) and evidence of post serpenitization deformation is represented by the shearing of some opaques (Takla and Suror, 1996).

Recently, Takla and Suror (1996) showed that some ophiolitic serpentinites from the Pan-African belt contain some Ni-sulphides and Ni-arsenides. Moreover, microprobe analyses of nickel sulphides showed that they carry Au up to 0.64 wt.% indicating that serpentinized ultramafics may represent an important parent lithology for gold (Takla and Suror, 1996). Similar to the Ni-sulphides, some of the Ni-arsenides contain traces of Au up to 0.031 wt.%.

During the Panafrican orogeny, serpentinites were metamorphosed to the epidote–amphibolite facies (Ghoneim et al., 1986). H_2O-CO_2 rich fluids continuously released within the greenschist facies and at the greenschist-amphibolite transition, move upward along thrusts and shear zones and react with the serpentinized ultramafic rocks, which are avid for carbonatization if compared with any member of the disseminated ophiolitic sequence located within the Panafrican belt.

Reactions take place between CO_2-rich fluids and the ophiolitic serpentinites resulting in their transformations into carbonates and quartz or talc and carbonates depending on temperature (Winkler, 1976):

$$1\ \text{Serpentine} + 3CO_2 \rightarrow 3\ \text{magnesite} + 2\ \text{Quartz} + 2H_2O \text{ at } P(\text{fluid}) = 2000 \text{ bars and temperature below } 350^\circ \text{ C} \quad (1)$$

$$2\ \text{Serpentine} + 3CO_2 \rightarrow 1\ \text{talc} + 3\ \text{magnesite} + 3H_2O \text{ at } P(\text{fluid}) = 2000 \text{ bars and temperature between } 350 \text{ and } 500^\circ \text{ C.} \quad (2)$$

Liberation of "available gold" from the ultramafic serpentinites took place concomitant with these transformations of ultramafic serpentinites (Boyle, 1961; Fyon et al., 1982). The leached gold moves, most probably with silica to other sites, certainly of low temperature, such as the highly sheared serpentinites and schistosity planes of graphitic and calcareous schists derived from these serpentinites, where it is deposited.

Sometimes, the intrusion of granites within these ophiolitic serpentinites plays an important role in localizing the auriferous quartz veins in such way that the difference in the competency between the granitic body with a brittle deformational characteristics and the surrounding ultramafic serpentinites with a ductile response to stress can lead to the development of a more extensive fracture pattern in the intrusion. This is clearly seen in El Sid gold deposit where veins and veinlets crossing the granites rapidly diminish into the ophiolitic serpentinites (Kochine and Basyuni, 1969).

3.2.3. Gold mineralization associated with porphyry copper mineralization

In Egypt, debate is still active about the possibility of finding porphyry copper in the Panafrican belt, although Ivanov and Hussein (1972) and Hussein (1990) suggested the possible occurrence of tow porphyry copper prospects at Hangalia and Um Garayat. Recently, Botros and Wetait (1997), based on geological, petrographical and geochemical studies, suggested that South Um Monqul gold prospect has many features in common with other porphyry copper systems in the world. The presence of acids–sulphate alteration (Botros, 1999), which is a common feature in porphyry deposits (Ashley, 1982; Sillitoe and Gappe, 1984; Sillitoe and Angeles, 1985; Sillitoe et al., 1990), also validated the suggestion of Botros and Wetait (1997).

Country rocks hosting the porphyry copper mineralization at UmMonqul prospect, are represented by a suite of intrusive rocks comprising granodiorite, biotite granite and granite porphyry, as well as, volcanic rocks pertaining to the Dokhan volcanics. These rock assemblage correlates excellently with those of active continental margin orogenic belts (Botros and Wetait, 1997) and most of the igneous plutonic rocks fall within the I-type grouping of the classification scheme of Chappel and White (1974) and the magnetite series of Ishihara's (1977) system (Botros and Wetait, 1997).

Gold mineralization connected with porphyry copper in South Um Monqul is observed in the following.

1. Minor secondary quartz veinlets linked with hydrothermal biotite in granite porphyry and dacite-rhyodacite porphyry (Fig. 12). These veinlets were the sites of intensive and active mining operations carried out by the old prospectors. Another site of auriferous quartz veinlets occurs at the contact zone between biotite and sericite-clay assemblage alterations, and it seems that this site was the location of old workings carried out by the old prospectors searching for gold as indicated by the presence of ruins of habitations and crushers in the near by of these sites. In the present paper, it is believed that this aureole of silicification is analogous to ore shell in the classical porphyry copper deposits. Copper values ranging from 3000 to 6000 ppm characterize this contact zone. In these veinlets gold occurs as disseminated specks associated with sulfides that are altered to goethite (Botros, 1991).

2. Barite-specularite veins linked to acid-sulphate alteration. In these veins gold is associated with the high sulfidation minerals enargite, bornite and chalcopyrite.

3. Minor specks dispersed in the magnetite, particularly when granite porphyry is the host rock (Fig. 13).

The eruption of the calc-alkaline Dokhan volcanics along active continental margins (Basta et al., 1980) and the belief that these volcanic rocks represent the surface expression of the calc-alkaline granites (El Gaby et al., 1988, 1990) let us probably be justified in saying that an ideal environment for the genesis of porphyry copper–gold mineralization in Egypt could exist. This is consistent with Hussein (1990) who mentioned that with continuing subduction, under a continental margin environment, the porphyry copper prospect (Hamash) and the precious metals (Au, Au–Ag) vein deposits were formed (Table 6).

3.2.4. Auriferous quartz veins connected with gabbros intruded by G-2 granites

This category of late-orogenic gold mineralization represents another style of vein-type mineralization connected with a specific rock unit in the Pan-African belt, i.e., the younger gabbros intruded by G-2 granites (Hussein et al., 1982).

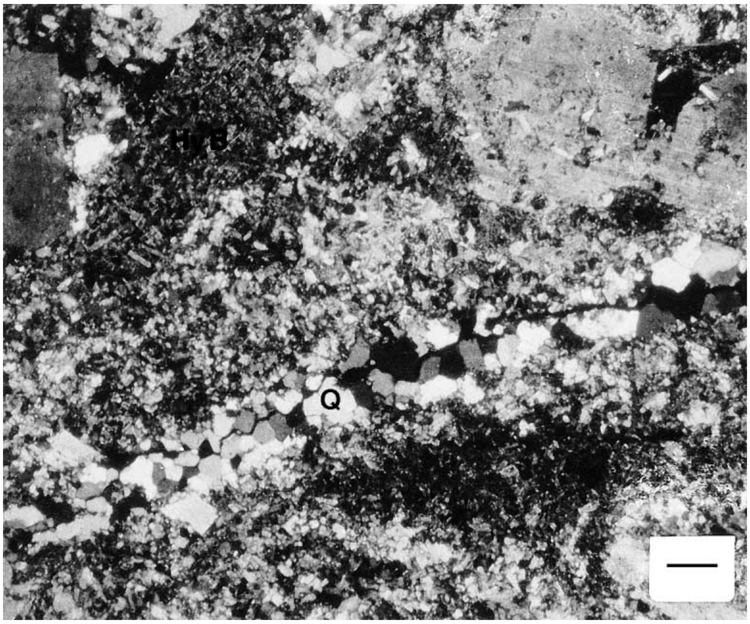

Fig. 12. Photomicrograph shows a clustering of hydrothermal biotite (Hy.B) in the form of a biotite crystal in rhyodacite porphyry. Notice the presence of secondary quartz veinlet (Q). Plane polarized light, crossed nicols, bar length represents 1.22 mm (from Botros and Wetait, 1997).

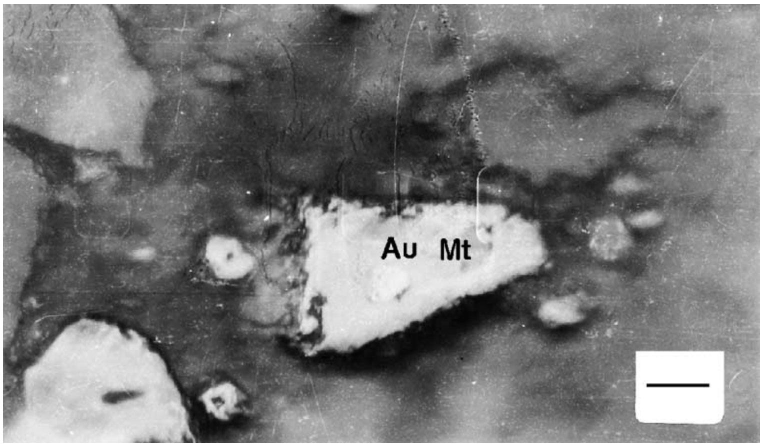

Fig. 13. Photomicrograph showing gold speck (Au) hosted in magnetite (Mt) host, Um Monqul gold prospect, Eastern Desert, Egypt. Reflected light, bar length represents 0.05 mm (from Botros and Wetait, 1997).

Takla (1971) and Takla et al. (1981) classified the gabbrocic rocks of the Eastern Desert into older and younger gabbros. They considered the older gabbros as regionally metamorphosed syn-tectonic plutonites, and some of them are parts of the ophiolites. The fresh gabbros (younger gabbros) on the other hand, represent continental margins magmatism that followed molass-type sediments, but older than G-2 granites (Takla and Hussein, 1995). The younger gabbros are represented by relatively small intrusive bodies comprising troctolites, olivine gabbro, hornblend gabbro and leuco gabbro (Takla et al., 1997a).

A relationship between gold mineralization and younger gabbros was observed in Um Eliga, Umm Tenedba, Atalla and Semna gold deposits (Takla et al., 1990, 1995a, 1997a; Basta et al., 1996). In these localities, Takla and his coworkers claimed that these gabbros are favorable source rocks for gold because of their intrinsically elevated gold concentrations. Gold in these rocks has average grades of 85 ppb in the heavy mineral concentrates of gabbro-norite in Um Eleiga area, 25 ppb in the heavy concentrates of hornblende gabbro-norite of Um Tenedba (Takla et al., 1995a), 510 to 710 ppb in gabbros of Atalla (Basta et al., 1996), and 360–710 ppb in gabbro of Semna gold deposit (Basta et al., 1996).

Recently, detailed field mapping, ore microscopic study and electron-microcrope analyses of younger gabbros from Atud gold deposit were carried out (Takla et al., 1998).

Field mapping revealed that gabbros of Atud gold mine can be classified into fresh olivine gabbro, altered gabbro and quartz-injected gabbro. The latter two varieties are abundant in the deeper levels of the shafts of the old gold mine where subsurface granite occurs and felsic stockworks at Atud gold mine increase downward (Takla et al., 1998).

Ore-microscopy of the different varieties of gabbro at Atud gold deposit revealed variation in sulphide mineralogy. Fresh olivine gabbro is characterized by the presence of pentlandite, chalcopyrite and pyrrhotite, whereas altered gabbro and quartz-injected gabbro, near the granite contacts, are dominated by pyrite and arsenopyrite.

Electromicrocrop analyses (Table 7) revealed that all sulphides of fresh olivine gabbro are auriferous and Ag-bearing. The highest Ag in sulphides is more concentrated in pyrrhotite in which Ag ranges from 100 to 680 ppm. The three auriferous sulphides of the fresh olivine gabbro contain appreciable contents of As and Sb which is not always common in mafic rocks (Takla et al., 1998). Highest As is recorded in exsolved chalcopyrite (up to 5720 ppm) which is positively correlated with the highest Au content of 710 ppm. Homogeneous pyrrhotite contains the highest Sb (300–310 ppm).

Pyrite and chalcopyrite recorded in both the altered and quartz-injected gabbro are also auriferous and Ag-bearing (Table 8). It is evident that pyrite is cryptically zoned with respect to Au, Ag, As and Sb. Gold con-

Table 7
Electron microprobe analyses (ppm) of the fresh gabbro from Atud gold mine, Eastern Desert, Egypt

Mineral	Au (ppm)	Ag (ppm)	As (ppm)	Sb (ppm)
Pyrrhotite				
Homogeneous crystal	150–170	190–200	–	300–310
Host for chalcopyrite	40–560	380–680	1290–1840	40–181
Host for pentlandite	340–430	100–140	1290–3520	30–270
Host for chalcopyrite–pentlandite	140–200	150–480	115–1720	0–130
Chalcopyrite				
Exsolved crystal in pyrrhotite	90–710	0–390	200–5720	30–210
Pentlandite				
Exsolved crystal in pyrrhotite	370–670	0–110	1420–3720	0–170

Data from Takla et al. (1998).

tent at the rim of pyrite from altered gabbro is the highest (790 ppm) whereas the highest As (9690 ppm) characterizes the pyrite rim in quartz-injected gabbro. The altered gabbro contains the highest Ag (670 ppm). Arsenopyrite composition also indicates cryptic zoning in which both As and Ni increases from core to rim. Following the same manner, Au and Ag increase toward the rim (up to 760 ppm Au and 660 ppm Ag). Sb is more concentrated at the cores of arsenopyrite (1040–1890 ppm) from the quartz-injected gabbro.

The new data of the trace element composition of sulphides from Atud gabbros proves their auriferous nature and the appreciable Ag content. It seems that the intrusion of a specific phase of the post-tectonic granite in a sulphide-bearing younger gabbro in the Eastern of Egypt results in the formation of quartz veins containing Au and Ag at the contact of both rocks (Takla et al., 1990). Quartz veins far from the granite–gabbro contact are unmineralized (Kamel et al., 1998). This setting (i.e., gabbro–granite contact) is found in a great number of ancient gold mines (Table 9). In this work, Atud gold mine is taken as a good example to this type of gold mineralization. In the deeper levels of the shaft in the mine area, one can notice: (a) injected quartz increases in the gabbro; (b) original primary silicate mineralogy of gabbro is greatly obliterated; (c) recrystallization of pyrite and introduction of As to the system (to form arsenopyrite) due to the presence of granite beneath gabbro; (d) pyrite shows the highest As (up to 9690 ppm) and Sb (up to 550 ppm) (Table 8) due to the closeness from the subsurface granite (Takla et al., 1998).

The mechanism adopted for the genesis of quartz veins located at the contacts between younger gabbro and granite relies on the assumption that the granite intrusion acts as heat engine and as a metal donor. The heat of the granite drives the convective cells to circulate through the fractured zone at the gabbro-granite contact (Takla et al., 1990), leaching gold and other elements and depositing it in structurally favorable sites (Fig. 14). The mobilization of gold took place during the oxidation of sulphides and the fracturing of the gabbro attendant upon the granite. The latter was emplaced at shallow depth as indicated by geothermometry of arsenopyrite in the quartz-injected gabbro (Takla et al., 1998) and the presence of porphyritic texture (Takla et al., 1990).

The role of granite as a source for metals is indicated by the high concentration of Sn and W (300 and 4000 ppm, respectively) in the heavy mi-

Table 8
Electron microprobe analyses (ppm) of the altered and quartz-injected gabbro from Atud gold mine, Eastern Desert, Egypt

	Au (ppm)	Ag (ppm)	As (ppm)	Sb (ppm)
Altered gabbro				
Pyrite				
Core	50	340	1370	0
Intermediate zone	120	340	2500	350
Rim	790	670	4710	400
Quartz injected gabbro				
Pyrite				
Core	120	60	4710	70
Rim	410	380	9690	550
Arsenopyrite				
Core	100–120	20–70	4000–4200	1040–1890
Rim	470–760	110–660	4000–4400	500–570

Data from Takla et al. (1998).

Table 9
Characteristic features of some important gold deposits located in and adjacent to gabbro-granite contacts from the Eastern Desert, Egypt

Deposit	Host rock	Lode type	Alteration assemblage	Ore minerals
Atud	Contacts between the gabbro and granite	Quartz veins enclosed in shear zones of pinch and swell structure; en echelon lenticular bodies of quartz; parallel veins and offshoots of quartz	Ch-Q-Ser-Carb-py	g + py
Um Tenedba (Kalib)	Gabbro and granite	Discontinuous quartz veins	Ser-Q-carb-Ch-Ep-py	g ± gn
Umm Rus	Veins are enclosed mainly within the granodiorite and pinch out in gabbro	Shear-zone vein arrays; quartz veins arranged en echelon	Ser-Epi-Carb-Ch-Q	g + py + apy ± sl ± gn ± cpy ± tet

Data from Kamel et al. (1998), Shazly et al. (1998) and Takla et al. (1995a, 1998).
Abbreviations: Q — quartz, Carb — carbonate, Ch — chlorite, Ep — epidote, Ser — Seircite, apy — arsenopyrite, cpy — chalcopyrite, gn — galena, py — pyrite, sl — sphalerite, tet — tetrahedite, g — gold.

neral concentrates of the quartz vein from Umm Tenedba gold mine (Takla et al., 1995a).

The activity of the circulated water within the fractured zone is attested by the abundance of chlorite, actinolite, tremolite, kaoline and injected quartz in the gabbroic rocks and white mica in the altered granite.

3.3. Gold mineralization accompanying post-orogenic stage

Gold mineralization connected with post-orogenic stage is represented by small amounts of the element in disseminations, stockworks and quartz veins of Sn–W–Ta–Nb mineralization. This is evidenced by the: (1) presence of traces of gold in tantalum-niobium mineralization hosted in apogranite at Abu Dabbab locality; (2) presence of gold (0.5–24 ppm) in rare-metals-bearing quartz veins at localities of Um Bissilla and Igla (Sabet et al., 1976).

Most of the rare-metal mineralization in the Eastern Desert is located in the so-called "apogranites". These are anorogenic intrusions with peraluminous A-type characteristics (Reno et al., 1993). Distinct features like sharp contacts with the surrounding rocks lacking of sodic metasomatism in the wall-rocks and the granite suggest their intrusive emplacement and magmatic character (Jahn et al., 1993).

The Ce/Nb–Y/Nb ratio suggests a melting of the lower crust (Reno et al., 1993), instead of a derivation from basaltic magma (Turner et al., 1992). The peraluminous A-type granites of the Eastern Desert are petrographically alkali feldspar granites with high contents of primary albite (20–90%). The other main minerals are quartz, microcline and muscovite. Common ore minerals are cassiterite and columbite–tantalite (Jahn et al., 1993).

No much is known about gold mineralization of this stage. However, fluid inclusion studies, conducted on some Sn–W-bearing quartz veins (Mohamed and Bishara, 1998), may be useful in defining the P–T conditions that prevail during rare-metal–gold mineralization.

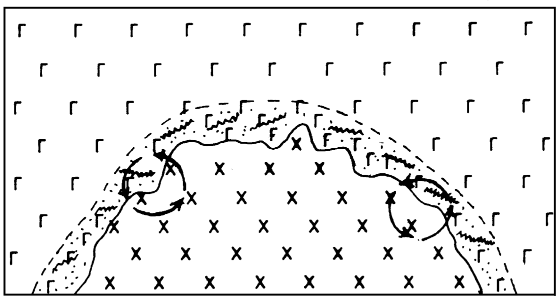

Fig. 14. Sketch diagram showing circulation of fluids in the contact zone between granite and gabbro, leaching available gold from the auriferous gabbro. [x x] Granite, [Γ Γ] Auriferous gabbro, [Γ:Γ] Contact zone (development of chlorite, actinolite, tremolite, kaoline and injected quartz in the gabbro and white mica in the granite), [—] Quartz veins, [↻] Direction of fluid circulation.

Results show that the mineralizing fluid was originally H_2O-CO_2 homogenous fluid composed of miscible carbon dioxide and aqueous salt solution. Sn and W might have been transported as chloride complexes (Mohamed and Bishara, 1998). Deposition took place at temperatures between 320 and 230 °C and at minimum pressure between 2.2 and 1.6 kbars for Sn-mineralization, and at temperature between 300 and 250 °C and pressure between 2 and 1.4 kbars for W mineralization (Mohamed and Bishara, 1998).

It is clear that, Sn and W were transported as soluble Sn–W chloride complexes and deposition took place at temperature range of 320–230 °C. The author speculates that these conditions were suitable for transportation and deposition of gold. This is supported by: (1) gold can be transported as chloride complex (Henley, 1973), (2) deposition of good is normally at 250–350 °C and at 1–2 kbars (Groves et al., 1989). The ultimate source of gold is currently uncertain. However, the possibility that available gold could be mobilized from gold mineralization styles formed in the earlier stages of the shield evolution by the hydrothermal fluids related to the A-type granite bodies is not precluded. The hypothesis that gold mineralization connected with post-orogenic stage may represent some remobilization of earlier gold is currently under review.

Gold mineralization associated with intra-plate G-3 granites corresponds to the Riphean–Lower Paleozoic epoch of gold mineralization adopted by Sabet et al. (1976).

4. Summary and conclusions

The present paper offers a correlation—though in general terms — of the major episodes of gold mineralization with the different tectonic–magmatic stages that characterize the evolution of the Nubian Shield in Egypt.

Three tectonic–magmatic stages with their specific gold mineralization are offered in this paper (Table 10). These are island-arc stage, orogenic stage and post-orogenic stage.

The formation of volcanic and volcaniclastic rocks of comparable composition in an ensimatic environment characterizes the island-arc stage. Gold mineralization connected with this stage is represented by exhalites typified by the stratiform to strata-bound auriferous Algoma-type BIF and its tuffaceous host rocks formed in the early stages of the arc development (immature arc). Gold hosted in volcanogenic Zn–Cu–Pb sulphide deposits formed in mature island arc also characterizes this stage.

Table 10
The different mineralization styles for gold deposits in Egypt and their place in the scheme of the evolution of the Nubian Shield

Stage	Style of mineralization	Tectonic environment	Remarks
Island-arc stage	(1) Gold hosted in Algoma-type BIF	Immature island-arc environment	Syngenetic mineralization
	(2) Gold hosted in tuffaceous metasedimentary rocks	Mature island-arc environment	
	(3) Gold hosted in volcanogenic massive sulphide deposits		
Orogenic stage	(1) Auriferous quartz veins hosted in metamorphic rocks and/or the granitic rocks surrounding them	Continental margin environment	Epigenetic mineralization
	(2) Auriferous quartz veins associated with porphyry copper mineralization		
	(3) Auriferous quartz veins at the contact between sulphide-bearing gabbro and granite		
	(4) Talc, talc-carbonate and quartz-carbonate rocks (listwaenites) along thrusts and shear zones in ophiolitic serpentinites		
Post-orogenic stage	Small amounts of the element in disseminations, stockworks and quartz veins of Sn–W–Ta–Nb mineralization	Within-plate environment	Epigenetic mineralization

Orogenic stage is characterized by the collision of arc–arc and/or arc–continent whereby the oceanic lithosphere underlying both the island arc and adjacent back-arc basin was obducted onto the continent, with disruption of the oceanic lithosphere forming dismembered ophiolitic components embedded in a volcano–sedimentary matrix. Subduction under the continent, on the other hand, generated calc-alkaline magmatism. The compressional deformation event that characterizes this stage was synchronous with regional metamorphism up to greenschist–amphibolite facies. Auriferous quartz veins that were the main target for gold since Pharaonic times represent gold mineralization associated with the orogenic stage. Other styles of gold mineralization are represented by gold mineralization along the sheared contacts of the ophiolitic serpentinites (listwaenites), auriferous quartz veins along the contacts between younger gabbros and G-2 granites, as well as, gold mineralization connected with porphyry copper deposits.

Post-orogenic stage is characterized by the intrusions of anorogenic sub-alkaline to per-alkaline plutons lumped together as G-3 granites (Hussein et al., 1982). Gold mineralization of this stage is represented by small amounts of the element in disseminations, stockworks and quartz veins of Sn–W–Ta–Nb mineralization.

The link between these tectonic–magmatic stages and gold mineralization can be used as a criterion at any exploration strategy for new targets of gold mineralization in Egypt.

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