Intrusion-related Gold Deposits in Egypt

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Abstract: Intrusion-related gold deposits (IRGDs) occur in the Eastern Desert (ED) of Egypt within magmatic districts that are exploited for tungsten and tin mineralization. IRGDs and intrusion-related rare metal deposits (IRRMDs) are almost invariably linked with the late to post collisional Younger Granites (YGs) that have three successive phases (I, II and III). At ~635–630 Ma, the ED underwent a transition in deformation style from compressional to extensional and a switch from subduction with crustal thickening to delamination with crustal thinning. This transition was concurrent with the emplacement of a short magmatic pulse (~635–630 Ma) that represents a transition between orogenic gold deposits and IRGDs. K-rich calcealkaline granites (phase I and II of the YGs) hosting IRGDs like the Hangalia deposit were emplaced during the time span 630–610 Ma. Alkaline magmatism began at 610 Ma, coexisting with the K-rich calce-alkaline magmatism over the 610–590 Ma time span, where the Fawakhir (598 ± 3 Ma) and Um Had (596 ± 2 Ma) granites that host the IRGDs were emplaced. In time, the alkaline magmatism became more alkaline giving rise to phase III of the YGs that hosts IRRMDs. A distinct metallogenic epoch comprising both IRGDs and IRRMDs, was undergoing extreme growth at ~600 Ma.

Key words: intrusion-related gold deposits, intrusion-related rare metal deposits, delamination, crustal melting, metallogenic epoch, ~600 Ma, Younger Granites

1 Introduction

Ancient Egypt has a long, deep and consistent relationship with gold. As one of the earliest metals to be discovered, the country became one of the first of many civilizations to boast a wealth of this valuable metal, believed to be the flesh of the sun god Ra, thus considered a symbol of eternal life.

Granitoid rocks constitute about 40% of the area covered by the Proterozoic shield rocks in Egypt, these granitoids ranging in composition from quartz diorite and tonalite, through granodiorite and quartz monzonite to true granites and alkaline-peralkaline granites (Hussein et al., 1982). Gold mineralization in the Eastern Desert (ED) of Egypt is closely associated with some of these granitic intrusions, in such a way that the mineralization is either hosted by or occurs immediately adjacent to these granitic intrusions (Botros, 2015a). Understanding the timing of gold mineralization with respect to the different magmatic pulses in the Eastern Desert of Egypt could lead to improved exploration criteria.

Some gold deposits in Egypt are classified as orogenic gold deposit (OGDs) (e.g. Zoheir, 2008) and some researchers believe that OGDs constitute the majority of gold deposits in Egypt (e.g. Zoheir, 2020). However, the term ‘orogenic’ gold has been progressively broadened to include deposits that are hosted in late to post-collisional granites (e.g. Gidami gold deposit; Abd El Monsef et al., 2018). Over time, significant ambiguity has become prevalent in defining the boundary between the OGDs and intrusion related gold deposits (IRGDs).

This paper compiles and synthesizes the existing geological, geochemical, geochronological and melt/fluid inclusions studies carried out on the late- and post-collisional Neoproterozoic granites in the Eastern Desert of Egypt. The time-space relationship between emplacement of the different phases of these granites and the hosting mineralization, as well as, the existing regional structure and the prevailing tectonic setting are also discussed. Moreover, the research is dedicated to answering the following questions: 1) why are some gold deposits concentrated in Wadi Allaqi in the south Eastern Desert at latitude 22°00′N (about 14 deposits) associated with a specific lithological assemblage, whereas others are clustered north of latitude 26°00′N (about 20 deposits) and are associated with a completely different lithological assemblage? 2) what is the relationship between IRGDs and rare-metal deposits in the Eastern Desert of Egypt? 3) is there a transitional regime between accretionary tectonics and escape tectonics in the Eastern Desert? and 4) is there a magmatic pulse representing a transition in the of the metallogeny of the Eastern Desert of Egypt from OGDs to IRRMDs?

2 Geological Setting

The Arabian-Nubian Shield (ANS) in NE Africa and W Arabia represents the northern part of the East African Orogen (EAO), which formed in the Tonian and...
Cryogenian accompanying terrane accretion around the Mozambique Ocean (Stern, 1994). The ANS is considered to be the largest tract of juvenile continental crust of Neoproterozoic age on Earth (Patchett and Chase, 2002; Hargrove et al., 2006; Liégeois and Stern, 2010). It represents a collage of volcanic arc terranes and associated ophiolite remnants, which amalgamated during the assembly of Gondwana and were then intruded by voluminous granitoids (Stern, 1994; Genna et al., 2002; Meert, 2003).

The northern segment of the ANS is exposed in the Eastern Desert of Egypt, which is dominated by juvenile crust that evolved between ~870 Ma and 550 Ma (Stern, 1994). The basement rocks in the Eastern Desert are restricted to the area between the River Nile and the Red Sea, where igneous and metamorphic rocks are widespread (Fig. 1). Three lithotectonic terranes have been identified in the Eastern Desert of Egypt (Stern and Hedge, 1985) namely the north Eastern Desert (NED) forming the northernmost outcrop to Safaga, the central Eastern Desert (CED) between Safaga and Marsa Alam and south Eastern Desert (SED) from Marsa Alam to the international border of Egypt at latitude 22°N (Fig. 2). These three domains reveal different aspects of the region’s protracted and intense Neoproterozoic episode of deformation and igneous activity (Stern, 2018).

In this paper, the international subdivisions for Neoproterozoic time, i.e. Tonian (1000–720 Ma), Cryogenian (720–635 Ma), and Ediacaran (635–541 Ma) are used to explain the tectonomagmatic evolution of the ANS. Based on radiometric ages and the distribution of diagnostic rock units in the Eastern Desert, the oldest rocks occur in the SED, while the youngest rocks occur in the NED (Stern and Hedge, 1985), although minor relics of Tonian age have also been identified in the south Um Mongol Cu-Mo-Au prospect in the NED (Abd El-Rahman et al., 2017). Tonian rocks (850–740 Ma) occur in the SED (Johnson, 2014), whereas the CED is mostly composed of a Cryogenian (~700–650 Ma) concentration of rocks of largely ensimatic character (Stern, 1981).

The NED is almost dominated by the Ediacaran events, represented by the abundance of Ediacaran post-amalgamation depositional basins (Johnson et al., 2011, 2013) filled with non-metamorphic clastic molasse sedimentary successions (Hammamat sediments) interfingering Dokhan volcanic rocks (Willis et al., 1988). Furthermore, granitoid rocks, particularly the younger granitoids are abundant in the NED, whereas there is a general lack of ophiolites.

The term Dokhan volcanic rocks refers to a varicoloured thick sequence of lava flows and pyroclastics of predominantly andesitic to rhyolitic composition in association with ignimbritic rhyolites (Basta et al., 1980; Stern and Gottfried, 1986). These volcanic rocks have been formed in subaerial environments and have medium-to high-K calc-alkaline affinities. According to Abdel Rahman and Doig (1987), the age for the Dokhan volcanics of the Gebel El Kharaza in the NED is 620 ± 16 Ma. SHRIMP U-Pb zircon dating carried out on two andesite samples from Gebel Dokhan yielded weighted average $^{206}\text{Pb} / ^{238}\text{U}$ ages of 593 ± 13 Ma and 602 ± 9 Ma (Wilde and Youssef, 2000). Based on SHRIMP U-Pb zircon dating, it was suggested that the Dokhan volcanic rocks of the Eastern Desert include two distinct age groups of an early volcanic pulse at 630–623 Ma and a late...
volcanic pulse at 618–592 Ma (Breitkreuz et al., 2010).

Debate over the formation of these volcanic rocks varies from it being in a compressional environment (El-Gaby et al., 1988; Hassan and Hashad, 1990; Abdel Rahman, 1996), in an extensional environment (Stern et al., 1984; Akaad, 1996; Fritz et al., 1996; Mohgazi, 2003), or during a transitional tectonomagmatic regime between extensional and compressional regimes (Ressetar and Monrad, 1983; Mohamed et al., 2000; Elwi et al., 2006).

The Hammatmat sediments are late-orogenic molasse-type fluvial sediments, marking a significant change in Pan-African tectonics; the end of the compressional and the onset of the extensional regime (Stern and Hedge, 1985). Most of the Eastern Desert molasse basins evolved between 650 Ma and 580 Ma in individual basins with different individual tectonic settings (Shalaby et al., 2006; Abd El-Wahed, 2010). Depending on their positions in the Pan-African Orogen of the Eastern Desert, three molasse-type basins are distinguished (Fritz et al., 1996): the first type is the foreland basins such as the Hammatmat Basin in which the sediments are deformed, metamorphosed and thrust over the Dokhan volcanics (Fritz et al., 1996; Andresen et al., 2009); the second type is the intramontane basins related to exhumation of the gneissic domes, being bounded by the sinistral northwest striking Najd fault system; e.g. El Mayah Basin (Shalaby et al., 2006) and showing pull-apart geometry; the third type is linked with low-angle normal faults to the northwest and/or southeast of the gneissic domes; e.g. the Kareim Basin, which reflects orthogonal northwest–southeast extension (Fritz et al., 1996). The presence of more than one type of molasse basin means that these basins derived their sediments from the Pan-African nappe assembly (i.e. Hammatmat Basin) or from gneissic domes connected with the Najd Fault System (i.e. Kareim and Mayah basins) (Fritz et al., 2002).

The CED is characterized by two major tectonostratigraphic units: the structural basement consisting of gneisses and amphibolites (El-Gaby et al., 1990; Loizenbauer et al., 2001) and the structural cover dominated by low-grade metamorphosed ophiolite slices, arc metavolcanics and arc metasediments (Wallbrucher et al., 1993; Fritz et al., 1996).

Gneissic domes in the CED, namely Meatiq, Sibai and Hafafit, were exhumed due to orogenic extensional collapse that followed thrusting and crustal thickening. Exhumation of gneissic domes in the CED was a long term tectonic process and was connected with intensive magmatic activity (Fritz et al., 2002). The protoliths of these gneissic domes consistently yield Neoproterozoic U-Pb zircon ages and the rocks have the neodymium, strontium, and hafnium isotope characteristics of a juvenile origin (Johnson, 2014). Gneissic domes are closely linked with the Najd Fault System (NFS), which is a complex set of left-lateral strike-slip faults and ductile shear zones that strike NW–SE across the Precambrian of Arabia and Egypt (Stern, 1985).

Ophiolitic serpentinites, which make up the base of the structural cover units, were formed in a fore arc environment (Azer and Stern, 2007), their protoliths being highly depleted harzburgites (Khalil and Azer, 2007). Volcano-sedimentary arc-related rocks that lie above the ophiolites were important supracrustal components of the CED. They are represented by thick sequences of greenschist-facies arc volcanics and associated wackes and volcaniclastics. In general terms, the island arc volcanic rocks (~750 Ma, Ali et al., 2009) are represented by submarine tholeiitic, calc-alkaline basalt and andesite with subordinate dacite, showing strong affinities with lavas from modern arcs and back-arc basins (Ali et al., 2009). Two interesting components are associated with the supracrustal volcano-sedimentary rocks in the CED: the Atud diamicite which is limited to the CED; the Algoma-type Banded Iron Formation (BIF) which occurs as sporadic deposits in layered volcanic and volcaniclastic rocks and localized in the central parts of the Eastern Desert with the exception of two occurrences at Semna and Abu Marawat further north (Botros, 1991). These BIFs seem to have formed ~750 Ma (Ali et al., 2009; Stern, 2018).

The SED lacks BIF and the Ediacaran Hammatmat sediments and Dokhan volcanic rocks found in the NED and CED. However, it is characterized by the presence of Volcanogenic Massive Sulphide Deposits (VMSDs) which are similar in many respects to the Canadian sulphide deposits (Hussein et al., 1977; Botros, 2003).

Traditionally in the Egyptian literature, two major groups of granites are known in the Eastern Desert. The first group is known as ‘Older Granites’ which have either a tholeiitic or transitional tholeiitic to calc-alkaline nature; the second group is known as ‘Younger Granites’ which have medium to high-K calc-alkaline and alkaline characteristics (Fig. 3).

The Younger Granites, which host the IRGDs (the main topic of this paper), are known as Gattarian granites in the records of the Egyptian Geological Survey. They are multi-phase, and three distinct successive phases have been distinguished and mapped separately in the Eastern Desert (Sabet et al., 1976b; Akaad et al., 1979; Akaad, 1996; Akaad and Abu El Ela, 2002). The first phase includes quartz diorites, tonalites, granodiorites and adamellites, while the second phase is represented by syenogranites and monzogranites, biotite-hornblende granites, granophyric and aplitic granites, felsite porphyries, granosyenites with dykes of plagiogranite porphyries, fine-grained granites, pegmatites and pegmatoid granites. The third phase comprises coarse-grained biotite microcline granites and leucocratic fine-to-medium-grained granites together with some aplites, felsites and granite porphyry dykes. Muscovite granite and apogranite massifs are also assigned to the third phase of the Younger Granites and represent the latest final sub-phases.

3 Grantoid Rocks in the Eastern Desert of Egypt

Intrusion-related gold deposits and rare metal deposits are almost invariably linked with the late to post-collisional granitoids. It is therefore appropriate to give a brief overview on the more common characteristics of the different groups of granitoid rocks in Egypt.
Granites within the Neoproterozoic basement of the Eastern Desert and Sinai (El-Bialy, 2020; modified after Farahat et al., 2011).

3.1 General scheme of the granitoid classification in Egypt

Several workers have attempted the identification and classification of the granites in Egypt. They were classified according to relative age (Older and Younger granites), dominant colour (grey, red and pink granites), type localities (Shaitian, Gattarian and Gharib granites) or their apparent relation to orogeny (syn-, late- and post-orogenic granites).

Hussein et al. (1982) classified these granites into three distinctive groups namely group I (G-1), group II (G-2) and group III (G-3). Most of the granites for which the terms ‘old’, ‘Shaitian’, ‘grey’ or ‘syn-orogenic granites’ were previously used, fall into group I (G-1) granites. They exhibit the following characteristics: calc-alkaline tendency, ranging from dioritic to granitic in composition, but mainly granodiorite, closely associated with island arc anodesites, formed in compressional environment and being I-type, magnetite series granites. G-2 granites are collision-related granites, having a calc-alkaline tendency and covering a narrow range of composition, which is always granitic. Most of the granites previously referred to as ‘younger’, ‘Gattarian’, ‘pink’, ‘red’ or ‘post-orogenic’ belong to this group. Granites of G-2 were formed in compressional environment and tend to be more S-type, ilmenite series granites. Granites of this group have been formed by the partial melting of the lower crust, probably with some addition from the mantle, during collision (suturing) at plate boundaries (Hussein et al., 1982). G-3 granites include the alkali or alkaline granites as well as a considerable proportion of those treated as ‘Younger Granites’ in the Egyptian literature. They were formed in an extensional environment within the plates subsequent to cratonization. Most of the Sn, W, Mo, Nb-Ta, REE, Be and F deposits are associated with the G-3 granites, but some of them may also be associated with G-2 granite masses (Hussein, 1990).

El-Gaby (1975) and El-Gaby et al. (1990) suggested that the Egyptian granites represent one continuous granite series, the early members are of tonalitic composition and the content of potash feldspar increases progressively in the later members, the last phases acquiring an alkaline to peralkaline affinity.

Maurice et al. (2013) classified the granitoids of Egypt into M-, I- and A-types. All older granitoids belong to the M- and the I-types. The M-type was generated during the early stages of subduction in an immature island arc setting, and is represented by trondhjemite and tonalites with subordinate quartz gabbro and quartz diorite. Trondhjemitic is similar to the low-K tholeiitic silicic volcanics, suggesting that the trondhjemite is the plutonic equivalents of the immature island arc extrusives, derived from a mantle source at the early immature island arc stage (Maurice et al., 2013). Calc alkaline ‘subduction-related’ I-type granitoids developed in a mature oceanic island arc setting, consequently, the subduction-related granitoids of Egypt could be classified into: M-type granitoids of immature oceanic arcs which are largely calcic and have characteristically low K$_2$O, as well as I-type granitoids of mature arcs, which are calc-alkaline and have higher K$_2$O when compared to the earlier tonalite. A-type granites show a composition ranging from alkali feldspar granite to syenite, being alkaline/peralkaline, anorogenic, and intra-plate granitoids (Maurice et al., 2013).

3.2 Change of the geochemical affinity of granitic magmatism

A change in the character of granitic magmatism is one of the most remarkable markers that heralds the end of a compressional tectonic stage in orogenic systems (Leite et al., 2007), and in the late orogenic stages, the transition from calc-alkaline magmatism, typical of the convergent period, to alkaline magmatism through high K-calc-alkaline magmatism is documented in the literature (e.g. Liégeois et al., 1987; King et al., 1997). Late orogenic histories are usually associated with extension where the lower crust and mantle lithosphere in these orogenic belts may have still been under compression while the upper crust was experiencing extension (Fritz et al., 2002). Hopper et al. (1995) explained that calc-alkaline magmatism can result from lithospheric extension in areas with a long history of prior subduction stages.
4 Genetic Relationships between Granites and Gold Mineralization in the Eastern Desert

The granitic rocks accompanying gold mineralization in Egypt are grouped into three main categories: 1) a calc-alkaline category dominate in the compressional stage; 2) a K-rich calc-alkaline category that characterizes the transitional tectono-magmatic regime between compression and extension, and 3) an alkaline category formed in an extensional environment within the plates subsequent to cratonization (Botros, 2015b).

Within these three main categories, the nature of the magmatism changed from tholeiitic→transitional (tholeiitic→calc-alkaline)→calc-alkaline→high K calc-alkaline followed by alkaline magmatism. Similarly, the tectonic regime in which these magmas were generated changed from immature to mature arcs, oceanic arc subduction-related magmatism, collision, post-collision to within-plate extension.

4.1 The calc-alkaline category

This covers the names previously used in the Egyptian literature e.g. ‘Older Granites’ (Hume, 1934; El-Ramly and Akaad, 1960), ‘Shahtian granites’ (Schurmann, 1953), ‘Grey granites’ (El Ramly and Akaad, 1960), ‘syn-orogenic granites’ (Sabet, 1961; El-Shazly, 1964), ‘tonalite, granodiorite-adamellite complex’ (Sabet, 1961, 1972), ‘G-Igraneites’ (Hussein et al., 1982). From the petrological point of view, this category includes trondhjemites, tonalites and granodiorites with minor granites (Moussa et al., 2008) and is considered to be metaluminous, I-type, magnetite series granites.

Emplacement of granites of this category was linked to three magmatic events at 850–800 Ma, 710–670 Ma and 630 Ma (Hassan and Hashad, 1990). The oldest magmatic event is the Shahtian event (850–800 Ma) in which the most deformed older granitoids in the south Eastern Desert; i.e. the Shahtian quartz diorite (801 ± 24 Ma) and Gebel Zabara foliated granite (850 Ma), were emplaced (Hassan and Hashad, 1990). The second magmatic event is provisionally called the Hafafit event, bracketed between 710 Ma and 670 Ma, this event covering the crust forming episode (715–700 Ma) of Stern and Hedge (1985) and the synorogenic pulse (705–680 Ma) of Lundmark et al. (2012). The third magmatic event suggested by Hassan and Hashad (1990) for the emplacement of granites pertaining to the calc-alkaline category, is referred to as the Mea’tiq event occurring at 630 Ma. The present author believes that the period of maximum convergence occurred at 650–640 Ma (Stern, 1994; Andresen et al., 2009), this time (i.e. ~630 Ma) representing the maximum crustal-mantle thickening and initiation of the delamination process (see later).

The calc-alkaline I-type granitoids were principally developed in a mature oceanic island arc setting, being emplaced in two successive events: 1) concurrent with the Cryogenian arc-arc collisional stage (~700–650 Ma) in which the arcs were accreted to form the composite arcs (proto arc of Johnson et al., 2011); and 2) concurrent with the approach between the composite arc terranes and West Gondwanaland in the Late Cryogenian–Ediacaran (~650–630 Ma) at the beginning of the assembly of Gondwana.

During these two successive events, the whole succession of the ophiolites and island arc association was dissected by many listric thrust faults causing repetitions, tectonic mixing (El-Gaby et al., 1988) and disruption of the oceanic lithosphere in the form of dismembered ophiolitic components (Akaad, 1996). Some gold deposits in the Eastern Desert having similar features to orogenic gold deposits were formed during these two successive compressional events and can be considered as orogenic gold deposits related to magmatism similar to the Koka gold deposit in Eritrea (Zhao et al., 2019).

Later, the compressional deformation event was synchronous with regional metamorphism to greenschist–amphibolite facies grade at ~633 Ma (Finger and Helmy, 1998; Abd El-Naby et al., 2000), dependent upon a short magmatic pulse at ~635–630 Ma that displayed a more alkaline character, if compared with earlier calc-alkaline magmatic pulses (Lundmark et al., 2012). The other category of OGDs in the Eastern Desert associated with this short magmatic pulse, was formed in such a way that the auriferous quartz veins are hosted either in the oceanic and island arc accretionary terranes that have been affected by tectonism and metamorphism and/or hosted in the accompanying K-rich calc-alkaline I-type granitoids (Botros, 2004). 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, 1995). Parent mineralizing fluids for these OGDs were mainly of metamorphic origin, the relatively high salinity observed in some fluid inclusions hosted in the auriferous quartz veins belonging to these orogenic gold deposits could be attributed to the mixing of these metamorphic fluids with magmatic fluids connected with the Older Granites that dominate in this environment (Botros, 2004). This is supported by oxygen and hydrogen isotopic studies that point to the overlap in the fields of metamorphic and magmatic waters (Botros, 2002, 2004).

4.2 K-rich calc-alkaline category

As previously mentioned, the magmatic pulse (~635–630 Ma) was a very short one and displayed a more alkaline character (Lundmark et al., 2012), when compared to earlier calc-alkaline magmatic pulses. This K-rich calc-alkaline pulse took place in the late orogenic stage in a transitional tectonomagmatic regime split between a collisional regime and the subsequent extensional regime. The existence of a transitional regime between accretionary tectonics and escape tectonics was suggested before, for the evolution of the ANS (Ressetar and Monrad, 1983; Mohamed et al., 2000; Eliwa et al., 2006; Botros, 2015a).

It seems that this short magmatic pulse represents a transition between OGDs linked with the calc-alkaline Older Granites and IRGDs linked with K-rich calc-alkaline Younger Granites in the Eastern Desert of Egypt (Botros, 2021). This transition from OGDs to IRGDs in the Eastern Desert at ~635–630 Ma is not entirely surprising, with many world-wide studies pointing to a number of orogenic gold deposits that have been re-
The OGDs–IRGDs transition in the Eastern Desert at ~635–630 Ma is compatible with the dating of the gold mineralization at 631 ± 12 Ma in neighboring Saudi Arabia at the An Najadi gold prospect (Walker et al., 1994). It should be noted that some orogenic gold deposits located in the western parts of the Afīf terrane in Saudi Arabia such as Ad Duwayhi, Sukhaybarat, Zalm and Bulghah have been re-interpreted as IRGDs (Doebrich et al., 2004), particularly those deposits occurring in the vicinity of tin and tungsten deposits.

El-Bialy (2020), in reviewing the recently published U-Pb zircon geochronology, came to the conclusion that emplacement of the post-collisional Younger Granites in Egypt has taken place throughout the prolonged 635–580 Ma period.

At ~630 Ma, possibly earlier in some parts of the Eastern Desert such as the El Sibai area (Fritz et al., 1996, 2002), due to significant crust–mantle thickening in the course of the late Neoproterozoic orogeny (Pallister et al., 1988; Kröner et al., 1992, 1994; Stern, 1994, 2002; Abdelsalam and Stern, 1996; Rino et al., 2008; Condic et al., 2009; Avigad and Gvirtzman, 2009), the mantle lithosphere was removed/delaminated from below the northern ANS, the ascending asthenosphere-derived magma underplating the crust, causing moderate-degree partial melting and the formation of a magma that with subsequent magmatic fractionation processes produced phase I and some sub-phases of phase II of the multi-phasic Younger (Gattarian) Granites in Egypt. Some sub-phases of these two phases belong to S-type granites and host Sn-W deposits in the Eastern Desert of Egypt (Hussein et al., 1982; Hussein, 1990), whereas other sub-phases belong to I-type granites and host economically important IRGDs.

Given the above, the K-rich calc alkaline category covers the late orogenic granites of El-Gaby et al. (1988), phases I and II of the Younger Granites (Sabet et al., 1976b; Akaad et al., 1979), the late East African post-collisional calc-alkaline magmatism (CA2) of Be’eri-Shlevin et al. (2009a, 2009b), the (G-2) suture-related S-type granites that host tin and tungsten deposits in Egypt (Hussein et al., 1982), and the slightly deformed to undeformed Hangalia Younger Granite (630 ± 5 Ma; Lundmark et al., 2012) that is metaluminous to slightly peraluminous in character, hosting the IRGD of Hangalia.

4.3 The alkaline category

The replacement of the cold dense mantle lithosphere by a hot and lighter asthenosphere during the delamination processes at ~630 Ma, caused surface uplift of the northern ANS to elevations of > 3 km (Avigad and Gvirtzman, 2009), thus promoting rapid erosional unroofing that led to decompression, this in turn facilitating the partial melting of the ANS upper mantle and lower crust to produce melts that intraplated the middle and upper crustal levels and formed by subsequent magmatic fractionation processes, the highly differentiated calc-alkaline granites and typical alkaline granites at 610 Ma (Avigad and Gvirtzman, 2009; Farahat and Azer, 2011). Previous studies revealed that calc-alkaline and alkaline magmas were coeval in the time interval of 610–590 Ma (Beyth et al., 1994; Meert, 2003; Avigad and Gvirtzman, 2009; Be’eri-Shlevin et al., 2009b), alkaline magma prevailing until ~580 Ma, producing the more potassic sub-phases of phase II and phase III sub-phases of the Younger Granites.

5 Tectonic Settings of Gold Deposits in Egypt

As an introduction to consideration of tectonic setting, it is appropriate to provide a brief overview of the tectonic settings of the other gold deposits in Egypt. Three types of gold deposits occur in the Eastern Desert of Egypt, these types being formed during distinctive stages characterizing the crustal evolution of the Egyptian segment of the ANS, are exhalative, orogenic and intrusion-related gold deposits. Size (where gold occurs as the primary commodity or as an accessory), type (i.e. the vein-type or disseminated), tectonic setting (i.e. compressional, transitional, tensional) and nature of mineralization (i.e. syngeneic or epigenetic) vary among these deposits (Botros, 2021).

Tectonically, volcanic rocks of the island arcs in the Eastern Desert show strong affinities to lavas from modern arcs and back-arc basins (Ali et al., 2009). The metabasalts and the meta andesites (~750 Ma, Ali et al., 2009; Stern and Ali, 2020), are overlain by tuffaceous metasediments which are intercalated with the BIF. Auriferous exhalative deposits were formed concomitant with the arc volcanicity at ~750 Ma as a result of interaction between volcanically derived fluids (hot brines) and sea water (Botros, 1995, 2003). These deposits include the auriferous Algoma-type BIF, where gold occurs in these deposits either restricted stratigraphically (strata-bound) within the BIF or is concentrated in quartz veins adjacent to or within the BIF (Botros, 1991, 1995; El Shimi, 1998; El Shimi and Soliman, 2002; Botros, 2021), as well as disseminated in the auriferous tuffaceous metasedimentary rocks (Botros, 1993) and gold-bearing VMSDs in the Um Samiuki and Hamama districts (Searle et al., 1976; Botros, 2003; Johnson et al., 2017; Bampton, 2017). The suggested age for these exhalites in the Eastern Desert is compatible with the age suggested for the genesis of the BIF in the Eastern Desert (Ali et al., 2009; Stern et al., 2013; Stern, 2018; Stern and Ali, 2020) and the ages suggested for other VMSDs in the ANS such as Jabal Sayid, Shaban and Baydan (~745 Ma); Shaib Lamisah and As Safra (~750 Ma) (Volesky et al., 2017 and references therein).

The term ‘orogenic gold deposits’ has been proposed by Groves et al. (1998) for gold deposits formed in accretionary and collisional orogens. Orogenic gold deposits in the Eastern Desert were formed in two successive epochs (Botros, 2021). The first epoch (~700–650 Ma) was linked to the arc-arc collisional stage while the second epoch was linked to the accretion of the composite arc terrane against the eastern flank of West Gondwanaland at ~650–630 Ma coeval with the beginning of the assembly of Gondwana. The arc-arc collisional stage was associated with an important epoch of plutonism represented by two magmatic pulses (~705–680 Ma and
The granitoids of this stage are trondhjemites, tonalites and granodiorites (Fowler and Hamimi, 2020). Arc-arc collision zones in the ANS are represented by ophiolite-decorated sutures from southern Egypt and Sudan into the western arc terranes of Saudi Arabia (Fowler and Hamimi, 2020). Collision between the south Eastern Desert-Midyan and the Gabbaga-Gebeit-Hijaz terranes along the ophiolite-bearing Yanbu-Onib-Sol Hamed-Gerf-Allagi-Heiani suture zone occurred at ~700 Ma (Ali et al., 2010; Johnson et al., 2011). Some gold deposits (e.g. Betam and Um Tuyor) are restricted to the western Allagi-Heiani suture that was formed at ~700 Ma. By the same token, in the south Eastern Desert of Egypt, the auriferous quartz veins traversing the volcanic-sedimentary rocks along the Wadi Beida gold prospect originated during arc-arc collision (Nano et al., 2002; Abdeen et al., 2008). No doubt, Wadi Beida auriferous quartz veins were subsequently deformed by another phase of deformation that extended the quartz veins in NNW–SSE direction, ultimately the veins becoming overprinted by sinistral strike-slip faults related to the Najd Fault System (Abdeen et al., 2008). In the first epoch of the orogenic gold deposits, calc-alkaline granite was the major fluid source for the mineralizing fluids, orogenic gold deposits forming in the arc-arc collisional stage could therefore be considered as orogenic gold deposits related to magmatism similar to the Morila orogenic gold deposit in South Mali (Hammond et al., 2011), orogenic gold deposits in the Birimian terrane of West Africa (Lawrence et al., 2013) and the Koka gold deposit in Eritrea (Zhao et al., 2019).

In the Eastern Desert, the period of maximum convergence occurred at 650–640 Ma (Stern, 1994; Andresen et al., 2009), and at ~630 Ma, the maximum crustal-mantle thickening took place and the delamination process was initiated. A transitional regime between accretionary tectonics and escape tectonics was suggested for the evolution of the ANS, as previously mentioned, this transitional regime being linked with a very short distinctive magmatic pulse (~635–630 Ma; Lundmark et al., 2012) that displayed more alkaline character when compared with earlier low K, calc-alkaline magmatic pulses, also being characterized by a transitional episode between OGDs and IRGDs formation (Botros, 2021). Geological and geochronological studies indicate that the timing of regional metamorphism in the Eastern Desert was about 633 Ma (Finger and Helmy, 1998; Abd El-Naby et al., 2000). In the transitional tektomagmatic regime, some orogenic-gold deposits were formed at ~633 Ma synchronous with the regional metamorphism (green-schist to amphibolite facies) resulting from the latest stages of emplacement of the K-rich calc-alkaline granitic series related to the Older Granites of the Eastern Desert. Orogenic gold deposits of the second epoch occur as auriferous quartz veins hosted either in the oceanic and island arc accretionary terranes that have been affected by tectonism and metamorphism and/or hosted in the accompanying K-rich calc-alkaline I-type granitoids (Botros, 2004). This explains why the majority of vein-type gold mineralization in the Eastern Desert is confined either to the intrusive masses of granodiorites and diorites (i.e. the ‘Older Granitoids’) or to schists (after volcanic and volcanoclastic rocks) in close proximity to these masses (El-Ramly et al., 1970; Botros, 2002). Parental mineralizing fluids for the second epoch of orogenic gold deposits were mainly of metamorphic origin. The relatively high salinity observed in some fluid inclusions hosted in the auriferous quartz veins belonging to these orogenic gold deposits could be due to mixing of these metamorphic fluids with magmatic fluids connected with the Older Granites that are predominant in this environment (Botros, 2004). This is supported by oxygen and hydrogen isotopic studies that pointed to the overlap in the fields of metamorphic and magmatic waters (Botros, 2002, 2004). As mentioned before, the OGDs–IRGDs transition episode in the Eastern Desert at –635–630 Ma is compatible with the dating of gold mineralization at 631 ± 12 Ma in neighboring Saudi Arabia at the An Najadi gold prospect (Walker et al., 1994).

IRGDs occur in the Eastern Desert of Egypt within magmatic districts that have been exploited for tungsten and tin mineralization (Botros, 2021), being linked with the late to post- collisional Younger Granites that have three successive phases (I, II and III). With the onset of the delamination process at ~630 Ma, the ascending asthenosphere-derived magma underplated the lower crust, triggering moderate-degree partial remelting of the lower crust, and the formation of a magma that with subsequent magmatic fractionation processes produced phase I and some sub-phases of phase II of the K-rich calc-alkaline Younger ‘Gattarian’ Granites within the time period ~630–610 Ma. Some varieties of these two phases belong to S-type granites which host some Sn-W deposits in the Eastern Desert of Egypt (Hussein et al., 1982; Hussein, 1990), whereas other varieties belong to I-type granites and host economically significant IRGDs. Alkaline magmatism started at 610 Ma, coexisting with K-rich calc-alkaline magmatism across the 610–590 Ma time span, when the Fawakhir (598 ± 3 Ma) and Um Had (596 ± 2 Ma) granites, hosting the IRGDs were emplaced. Over time, the alkaline magmatism changed to become more alkaline giving rise to phase III of the Younger Granites that hosts IRRMDs.

6 Intrusion-related Gold Deposits (IRGDs)

6.1 Historical review

Thompson et al. (1999) distinguished IRGDs in districts that lacked copper, but were known for W and Sn deposits. IRGDs are low-grade, large-tonnage deposits (Lang et al., 2000), associated with intrusions that are more felsic, more reduced and are partly of S-type character when compared to gold deposits associated with chalcophile oxidized magmas associated with porphyry deposits (e.g. Sillitoe, 1991, 1995). Lang et al. (2000) introduced the term intrusion-related gold systems (IRGSs), ‘system’ being used to draw attention to the wide range of associated gold deposit styles within this class of intrusions. Thompson and Newberry (2000) introduced the term ‘reduced’ IRGS to highlight the importance of the
reduced oxidation state of the granitoids (low $/O_2$) and the associated exsolation fluids in this class of gold deposits, when compared with granitoids associated with porphyry occurrences.

6.2 Characteristics of IRGDs

In this work, IRGDs pertain to the world-wide class known in geological literature as reduced intrusion related gold systems (IRGS), taking into consideration that each deposit has its own unique characteristics and not all deposits show all properties of any particular classification. 

Sillitoe (1991), Hollister (1992), Newberry et al. (1995), Lang et al. (1997), McCoy et al. (1997), Thompson et al. (1999), Lang et al. (2000), Thompson and Newberry (2000), Goldfarb et al. (2000) and Baker and Lang (2001) summarized the characteristic features of IRGDs as the following:

- Tectonic setting well away from convergent plate boundaries (continental setting).
- Spatial and temporal association with predominantly metaluminous to weakly peraluminous intrusions connected with subalkalic intrusions of felsic to intermediate composition that lie near the boundary between the ilmenite and magnetite series.
- Located in magmatic districts best or formerly known for tungsten and/or tin deposits.
- Having a metal assemblage characterized by Bi, As, and Te, with less consistent anomalies for U, Mo, Sn, Pb, and Sb.
- Gold deposition took place from dilute CO$_2$-rich fluid at minimum temperatures of 330 $\pm$ 20°C and pressures of 1 $\pm$ 1.5 kbars.
- Having a low sulphide mineral content, mostly < 5 vol%, with a reduced mineral ore assemblage that typically includes arsenopyrite, pyrrhotite, pyrite and loellingite, lacking magnetite or hematite.
- Having comparatively restricted zones of predominantly fracture controlled hydrothermal alteration dominated by K-feldspar, albite or muscovite.
- Disseminated and vein deposits of this class may occur outside contact aureoles, up to 3 km from the intrusive centres.
- The intrusions throughout the belt were emplaced over a short time interval, and are characterized by moderate to extensive crustal involvement.

7 IRGDs in the Eastern Desert of Egypt

7.1 Introduction

In the Eastern Desert of Egypt, particularly in the northern part of the CED and NED, there are some IRGDs that were previously classified as orogenic gold deposits. These IRGDs are hosted in late to post-collisional granites belonging the Younger Granites in Egypt, particularly those emplaced at 610–590 Ma, concurrent with the deposition of the Hammamat molasse sediments and the eruption of the late-orogenic Dokhan volcanic rocks (Botros, 2021). Most of these deposits occur in magmatic districts formerly known for tungsten (e.g. in Abu Hammad, Abu Kharif, El Dob, Fatira El Beida, Um Bisilla, G.Maghrabiya, Zargat El Naam, etc.) and/or tin deposits (e.g. Kab Amiri, Hamr Waggad, Iglia, Mueilha, etc.).

7.2 Timing of transition from OGDs to IRGDs in the Eastern Desert

Although debate surrounds the timing of the collision between the accreted Pan-African terranes and West Gondwanaland, the general consensus is that the collision occurred between 650 Ma and 620 Ma (Schandelmeyer et al., 1987; Kröner et al., 1994; Sultan et al., 1994; Finger and Helmy, 1998). Moreover, a growing body of evidence indicates that the ANS crust at ~630 Ma was increasingly sandwiched between the colliding fragments of East and West Gondwana (Stern, 1994; Jacobs and Thomas, 2004; Avigad and Gvirtzman, 2009; Be'eri-Shlevin et al., 2009b; Johnson et al., 2011; Fritz et al., 2013). From 630 Ma, the orogen evolved from accretionary tectonics to escape tectonics characterized by lithospheric delamination (Avigad and Gvirtzman, 2009) in the presence of the strike-slip Najd shear system (Meyer et al., 2014). Also, there is firm geological and geochronological evidence that the timing of regional metamorphism in the Eastern Desert was around 633 Ma (Finger and Helmy, 1998; Abd El-Naby et al., 2000).

The ~635 Ma to ~630 Ma magmatic pulses (Lundmark et al., 2012) is an important one in the ANS in the Late Cryogenian (Ali et al., 2012a). As mentioned before, this short magmatic pulse represents a transition from OGDs to IRGDs in the Eastern Desert of Egypt as indicated by the presence of native bismuth, ferrocolumbite, fergusonite and uraninite in the gold-bearing quartz veins of the Hangalia gold deposit (Raslan and Ali, 2010) that is hosted by leucogranite emplaced during the time of this pulse (Lundmark et al., 2012).

This transition in the Eastern Desert from orogenic gold deposits to intrusion-related gold deposits at ~635–630 Ma is consistent with the study of Zoheir et al. (2019b) that revealed the formation of OGDs in the Eastern Desert of Egypt within a restricted time period at the end of the Cryogenian (720–635 Ma) and the beginning of the Ediacaran (635–541 Ma). This OGDs-IRGD transition took place during an episode characterized by: 1) transition in deformation style from compressional to extensional; 2) switching from subduction and crustal thickening to delamination and crustal thinning; and 3) transition in magmatism from arc-related, syntectonic Older Granites to late to post-tectonic multi-phasic Younger Granites in the Eastern Desert of Egypt.

It is proposed that under a transitional tectonomagmatic regime between the collisional and subsequent extensional regimes, some orogenic-gold deposits were formed synchronously with regional metamorphism (greenschist to amphibolite facies) at ~633 Ma, subject to the short K-rich calc-alkaline magmatic pulse at ~635–630 Ma.

7.3 Delamination of the lithosphere in the Eastern Desert and emplacement of the Younger Granite phases

In the early stages of the ~630 Ma delamination, it is believed that the upwellings asthenosphere released a
steady stream of volatile-rich fluids which transferred water, halogen, High Field-Strength Elements (HFSEs), Rare Earth Elements (REEs) and alkaline elements from the deep asthenosphere to the shallow lithosphere (Huang et al., 2014). Such mantle degassing processes locally ‘soaked’ the lower crust, inducing enrichment of fluorine, alkalis, HFSEs and REEs in the crust (Fig. 4). The formation of this fertilized crust is consistent with previous studies (e.g. Bailey, 1980; Woolley, 1987; Zou et al., 2000; Hou et al., 2010; Martin, 2006, 2012) that pointed to the presence of districts of extensional environments acting as loci of Earth’s degassing, where a steady stream of fluid rose ahead of the upwelling asthenosphere.

With the onset of the delamination process, the ascending asthenosphere-derived magma underplated the lower crust, causing moderate partial remelting of the fertilized protolith, forming a magma that with subsequent magmatic fractionation processes produced phase I and some sub-phases of phase II of the multi-phasic Younger ‘Gattarian’ Granites (e.g. the Hangalia granite, hosting Hangalia gold deposit, linked with the ~635–630 Ma magmatic pulse of Lundmark et al., 2012). The presence of native bismuth, ferrocolumbite, fergusonite and uraninite in the gold-bearing quartz veins hosted in the Hangalia granite (Raslan and Ali, 2010) confirm the formation of magma by partial melting of the fertilized protolith.

In the Eastern Desert of Egypt, it has been suggested that phase I and phase II of the Younger Granites, more specifically the late most leucocratic sub-phases (small intrusions and dykes) attain rare earth and rare metal specialization, where they bear cassiterite, zircon, xenotime, monazite, orthite, topaz, sometimes tourmaline and rarely columbite (Sabet et al., 1976a).

It appears that, large volumes of late-collisional calc-alkaline granites comprising phase I and some sub-phases of phase II pertaining to the multi-phasic Younger Granites, were emplaced within the time period of ~630–610 Ma and are related to whole-scale lower crustal melting due to asthenosphere derived magma underplating concomitant with the lithospheric delamination.

At ~610 Ma, typical alkaline magmatism was coevally-generated with calc-alkaline magmatism and they progressed together in the time interval 610–590 Ma (Beyth et al., 1994; Meert, 2003; Avigad and Gvirtzman, 2009; Be’er-Shlevin et al., 2009b). From ~590 Ma, the third phase of the Younger Granites represented by G-3 granites (Hussein et al., 1982), was emplaced and a conspicuous epoch of ore formation for rare metals (Be, Ta, Nb, Li, Sn, W, Mo, U), spatially and genetically related to this third phase, particularly their latest subphases were formed (Sabet et al., 1976a). This is indicated by the study of Kuster (2009), that pointed to the formation of rare metal mineralization hosted in the granites of the Eastern Desert of Egypt close to 600 Ma.

It is clear that both asthenospheric uprise and erosional decomposition were responsible at various times for the generation of the widespread three phases pertaining to the late collisional calc-alkaline granites and post-collisional alkaline granites. During the time period 630–610 Ma, the ascension of the asthenosphere-derived magma underplated the lower crust, causing its partial melting and generating the calc-alkaline granites (Avigad and Gvirtzman, 2009; Farahat and Azer, 2011; Azer and Farahat, 2011; Farahat et al., 2011; Eliwa et al., 2014a, 2014b; Sami et al., 2017, 2018; Khalil et al., 2018). At 610 Ma (the culmination of the delamination process) due to erosional decomposition, the upper mantle and lower fertilized crust were melted and produced melts that intraplated the middle and upper crustal levels, forming through subsequent magmatic fractionation processes, the highly differentiated calc-alkaline granites, with extended fractionation of volatile-enriched granitic magmas producing more alkaline granites hosting rare-metal deposits (Kuster, 2009). Examples of late and post-collisional granites in the Eastern Desert include; 1) two mica granites in Deleihimmi area (Farahat et al., 2011); 2) syenogranite in El Ineigia area (Sami et al., 2017); 3) Sn-Ta-W-bearing albite granite in Abu Dabbab (Mohamed, 1993; Kuster, 2009); and 4) alkali granite in the Humr Akarim and Humr Mubkid areas (Ali et al., 2013).

7.4 The importance of both calc-alkaline and alkaline magmas coexisting during the 610–590 Ma time span

Typical alkaline magmatism started contemporaneously with the peak in calc-alkaline felsic activity, lasting until 580 Ma (Be’er-Shlevin et al., 2009a, Hamimi et al., 2019). The transition from late- to post-collisional granites at 610 Ma, and the coexistence of both calc-alkaline and alkaline magmas over the 610–590 Ma time span was significant from the economical point of view, as indicated by the Re-Os age of 601 ± 17 Ma on arsenopyrite intimately associated with gold particles in quartz veins traversing monzodiorite in the Fawakhir- El Sid gold district (Zoheir et al., 2015), as well as the 40Ar/39Ar plateau age of hydrothermal white mica (601 ± 5.5 Ma, 2σ) disseminated in gold-bearing quartz veins traversing monzogranite at the Atalla mine (Zoheir et al., 2018a). Gold mineralization during in this episode was hosted in the plutons of monzogranite-syenogranite and biotite-alkali granite in both the Fawakhir (598 ± 3 Ma; 207Pb/206Pb, Andresen et al., 2009) and Um Had (596 ± 2 Ma; ID-TIMS, Andresen et al., 2009) districts. The emplacement of these plutons was concurrent with the fourth (610–604 Ma) and fifth (600–590 Ma) magmatic
pulses of Lundmark et al. (2012) and contemporary with the deposition of the Hammatat Group sediments, eruption of the late-orogenic Dokhan volcanics (Wild and Youssef, 2000, 2002) and the exhumation of mid-crustal gneisses along the Eastern Desert shear zone (Lundmark et al., 2012).

In the light of the available robust age dating, it is clear that IRGDs, at least in central part of the Eastern Desert were successively formed concurrent with the emplacement of various phases of the Younger Granites. The Um Rus tonalite-granodiorite (i.e. phase I of the Younger Granites) hosting the Um Rus gold deposit was emplaced at 643 ± 9 Ma (Zoheir et al., 2019a) during the slightly earlier time of the extensional regime, as with the El Sibai area (Fritz et al., 1996, 2002). It is worth mentioning that the Ad Duwayhi IRGD in Saudi Arabia (the Arabian Shield) is closely associated in time and space with the emplacement of a late- to post-orogenic granitic body (659 ± 7 Ma) and coeval quartz porphyry dikes (646 ± 11 Ma) (Doebrich et al., 2004). Ages of 655.6 ± 2.7 Ma and 649.9 ± 2.3 Ma, were considered robust ages of intrusion-related gold mineralization at Ad Duwayhi (Doebrich et al., 2004).

The emplacement of the Um Rus tonalite-granodiorite hosting the Um Rus IRGD was followed by the emplacement of the Hangalia granite-hosting the Hangalia gold deposit at 638 ± 5 Ma, based on U-Pb data (Lundmark et al., 2012). The Atalla intrusion was emplaced at 615 ± 9 Ma (Zoheir et al., 2018a) and during the 610–590 Ma time span, Fawakhir (598 ± 3 Ma; Andresen et al., 2009) and Um Had (596 ± 2 Ma; Andresen et al., 2009) were both emplaced.

7.5 Does the Sukari gold deposit belong to the IRGDs?
At present the Sukari gold mine (latitude 24°56′30″N and longitude 34°42′27″E) is the single major gold mine in production in the Eastern Desert. In 2018, Centamin produced 472,418 oz of gold according to the 2018 Annual Report on the web site. The mineralization is closely associated in time and space with the emplacement of a late- to post-orogenic granitic body (659 ± 7 Ma) and coeval quartz porphyry dikes (646 ± 11 Ma) (Doebrich et al., 2004). Ages of 655.6 ± 2.7 Ma and 649.9 ± 2.3 Ma, were considered robust ages of intrusion-related gold mineralization at Ad Duwayhi (Doebrich et al., 2004).

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The single factor that inclined some authors to assign the Sukari gold deposit to the category of orogenic gold deposits rather than IRGDs was the lack of proper dating of the Sukari pluton. Based on Rb-Sr isotope data, Ghoneim et al. (1999) suggested a crystallization age of 559 ± 6 Ma for the pluton, followed by Na metasomatism at 520 ± 11 Ma. The Sukari pluton has been interpreted as one of the Older Granites by Akaad and Noweir (1980), and as a Younger Granite by Sharara (1999) and Helmy et al. (2004). Lundmark et al. (2012), based on U-Pb ID-TIMS geochronological data dated the Sukari granodiorite at 689 ± 3 Ma, consequently assigning it to the Older Granite category. This age estimate was challenged by Zoheir et al. (2019a) not for the accuracy of the technique used, but because they claimed that the location of the Sukari sample used in Lundmark et al. (2012) was actually from a locality several tens of kilometres from the Sukari intrusion and the age should therefore be cross-checked before any attempt was made to interpret the given age.

The geological map of Jabal Hamatah, scale 1:250,000, published by the Egyptian Geological Survey and Mining Authority (EGSMA, 1997) in collaboration with the British Geological Survey (BGS) indicated the presence of the Sukari gold deposits in post-tectonic pink, undeformed monzogranite and alkali feldspar granite.

In the light of the available petrological and geochemical studies carried out on the Sukari granite (Ali et al., 2016; Mohamed et al., 2019), and the published map of Jabal Hamatah (EGSMA, 1997), it is hard to argue against the necessity of re-classifying the Sukari granite and affiliating the intrusion with the late- to post-orogenic magmatism in the Eastern Desert of Egypt, consequently assigning Sukari gold deposit to the category of intrusion-related gold deposits in Egypt. The presence of the Sukari deposit, as shown in the sketch map (Fig. 5) in the vicinity of the Iгла district (tin-tungsten-rare metals) in the north and the Zabara district (beryl tin-rare metals) in the south confirms and supports this reclassification.

7.6 Patterns of IRGDs in the Eastern Desert of Egypt
Taking into consideration that disseminated and vein deposits in IRGDs may occur outside the contact aureoles, up to 3 km from the intrusive centres (Thompson et al., 1999), it is therefore un surprising that IRGDs in Egypt reveal some patterns of gold mineralization. These patterns are represented by auriferous quartz veins hosted in the late to post-collisional granites (e.g. Sukari, Atalla, Um Samra- Um Bakra and Gidami gold deposits and occurrences), auriferous quartz veins hosted in the contact zone between undeformed younger gabbros and a specific phase of post collisional granites (e.g. Atud and Um Rus deposits), auriferous quartz veins hosted in the contact zone between the Dokhan volcanics and post-collisional granites (e.g. Hammadm gold occurrence), auriferous quartz veins hosted in the contact zone between Hammamat sediments and post-collisional granites (e.g. Abu Garahish gold occurrence), in addition to auriferous quartz veins hosted in the contact zone between the post-collisional granites and the ophiolitic serpentinites (e.g. El Sid deposit), and auriferous quartz veins hosted in the
contact zone between the post-collisional granites and island arc assemblages and ophiolitic melange (e.g. Sharm El Bahari occurrence).

7.7 Recent discoveries of IRGDs in the Eastern Desert of Egypt

Recently, more than one company has received licenses to search and exploit gold in the Eastern Desert of Egypt. Reports issued by the field operators of these companies, supported by reliable chemical analyses point to the presence of IRGDs within their concessions. For example, Thani Stratex Resources Limited (TSRL) (http://thanistratex.com) works in the Hodein concession (~1,190 km$^2$) located in the Red Sea settlement of Shalatein. Gold mineralisation in this concession is hosted in the Anbat-Shakoosh belt, and mineralization at all prospects within the belt displays a gold-arsenic-molybdenum signature characteristic of intrusion related systems as reported by TSRL on the web site. Aton Resources Inc or the Aton Resources Company (ARC) (https://www.atonresources.com) also works in Egypt and owns the Abu Marawat concession (596.3 km$^2$) located in the central Eastern Desert of Egypt. ARC has identified numerous gold occurrences throughout the entirety of the concession area, and has undertaken preliminary exploration in these occurrences, such as Bohlog, Abu Garahish, Semna East and Sirkis, all of which point to the presence of intrusion related gold systems. Figure 6 shows the boundary of the ARC concession area, with only the new discoveries that point to the presence of IRGDs being plotted.

It should be noted that, out of the intrusion-related gold mineralisation discovered in the concession area of ARC, other types of mineralizations related to the late to post-collisional granites occur, including the tungsten-bearing Abu Garida granite, fluorite veins in the Garida granite, uranium mineralization in the Eredia granite and niobium-tantalum mineralization associated with the Kab Amiri granite in the south of the concession.

7.8 Characteristics of intrusion-related gold deposits in Egypt

IRGDs in the Eastern Desert of Egypt have the following characteristic features:

(1) The mineralization is spatially and genetically related to the multi-phasic Younger Granite in Egypt as indicated by the presence of the auriferous quartz veins traversing the Um Rus tonalite-granodiorite (phase I of the Younger Granites), Hangalia biotite granite (phase II of the Younger Granites) and Um Samra syenogranite to alkali feldspar granite (phase III of the Younger Granite).

(2) The mineralization is late with respect to peak metamorphism, there being a general consensus that timing of regional metamorphism in the Eastern Desert was at about 633 Ma (e.g. Finger and Helmy, 1998; Abd El-Naby et al., 2000).

(3) IRGDs were successively formed concomitant with the emplacement of the various phases of the Younger Granites, beginning with the transitional episode at ~635–630 Ma, where some OGDs and IRGDs were formed, then linked with K-rich calc-alkaline granites being emplaced in the ~630–610 Ma time span as a result of lower crustal melting due to asthenosphere-derived magma underplating concurrent with lithospheric delamination and terminated by the coeval emplacement of calc-alkaline and alkaline granites in the 610–590 Ma time span due to erosional decompression and contemporaneous with the deposition of the Hammamat sediments and the eruption of the late-orogenic Dokhan volcanics and exhumation of mid-crustal gneisses.

(4) The mineralization comprises gold-bearing quartz stockworks and veins, sometimes the mineralization is enclosed in aplitic dykes, as in the Gidami gold mine area (Abd El Monsef et al., 2018), diorite porphyry dykes, as in
(5) The causative intrusions for these deposits pertain mainly to both phase I and phase II of the Younger Granites in Egypt, sometimes belonging to the third phase of these post-collisional granites. In Sukari, the causative intrusion is represented by alkali feldspar granite, syenogranite and monzogranite (Mohamed et al., 2019); in the Atalla gold deposit, the causative intrusion is monzogranite (Zoheir et al., 2018b). Monzogranite through syenogranite to alkali feldspar granite with gradational contacts is the causative composite intrusion in the Um Samra-Um Bakra district (Ibrahim et al., 2017), tonalite–granodiorite is the causative intrusion in the Um Rus gold deposit (Zoheir et al., 2019a) and in Wadi Hammad, the causative intrusion is monzogranite (Nasr et al., 1998).

(6) Geochemically, these granitoids are metaluminous-to weakly peraluminous in character (Mohamed et al., 2019; Zoheir et al., 2019a). The weakly peraluminous granites are marked by the presence of as much as 2.3 wt% normative corundum (e.g. Um Rus gold deposit, Zoheir et al., 2019a). The metaluminous and peraluminous character of the causative intrusions is reflected in their mineralogy, which includes variable amounts of hornblende and biotite.

(7) The auriferous veins in the IRGDs are associated with restricted zones of sericitization and silicification (e.g. Atalla, Sukari, Um Samra–Um Bakra area), and in some deposits (e.g. Gidami) kaolinitization and carbonatization are also noted (Abd El Monsef et al., 2018).

(8) Mineralogy of the veins and stockworks in the IRGDs includes pyrite, arsenopyrite, with less common sphalerite, chalcopyrite, galena, and gold. Rare hesseite and Bi-galena are associated with sphalerite and gold in some deposits (e.g. Atalla). Primary loellingite hosted in late arsenopyrite is recorded in the auriferous quartz veins of the Um Rus gold deposit (Zoheir et al., 2019a). Stibnite was identified only by SEM analysis and occurs as fine-grained disseminations in the fractures of the quartz veins of the Um Samra–Um Bakra area (Shazly et al., 1998). Molybdenite is recorded in the Gidami auriferous quartz veins (Abd El Monsef et al., 2018) and in the smoky quartz veins in the Atalla gold deposit (Basta et al., 1996), tungsten is recorded in the Abu Garahish gold occurrence (Klemm and Klemm, 1994), cassiterite is recorded in the quartz veins of the Um Rus gold deposit (Kamel et al., 1992) and fluorite is recorded in the Gidami auriferous quartz veins (Abd El Monsef et al., 2018).

(9) Magnetite is absent or rare in the intrusions, whereas ilmenite is the main iron oxide mineral phases in some granites (e.g. the Gidami gold mine, Abd El Monsef et al., 2018), suggesting that the intrusions are moderately reduced and assigned to the ilmenite series.

(10) Gold occurs mainly in the quartz veins and alteration zones, always as disseminations in country rocks like the epidiorite-diorite complex in the Um Samra-Um Bakra area, where some concentrations ranging between 0.3 and 0.8 g/t are recorded (Mansour and Zhoukov, 1973).

(11) Fluid inclusion studies reveal that the mineralizing fluid was originally homogeneous aqueous-carbonic with variable salinities, e.g. salinity in the inclusions of Atalla deposit is ~2 equiv. mass % NaCl (Zoheir et al., 2018b); 0.7 equiv. wt% NaCl in fluid inclusions in the early Fe-As ± Cu-sulphide stage and higher salinities of up to 15 equiv. wt% NaCl in the late paragenesis of the Zn-Pb-Sb stage in the El Sid deposit (Zoheir and Moritz, 2014); in the range 0.7–3 equiv. wt% NaCl in Um Samara (Shazly et al., 1998); in the range 4.5–8.9 equiv. wt% NaCl in Um Bakra (Shazly et al., 1998); in the range 2.8–8.2 equiv. wt% NaCl in the Atud deposit (Harraz, 2002).

(12) Gold mineralization took place at a variable range of temperatures during the system’s cooling and mixing of the aqueous-carbonic fluids by meteoric water, e.g. deposition occurred in the range 96–188°C in Sukari (Helmy et al., 2004); in the range < 200°C to ~280°C in Atalla deposit (Zoheir et al., 2018b); in the range 290–310°C in Um Samra (Shazly et al., 1998); within the range 270–300°C in Um Bakra (Shazly et al., 1998); in the range 300°C to 350°C in El Sid deposit (Zoheir and Moritz, 2014); in the range 270–300°C in Gidami gold deposit (Abd El Monsef et al., 2018) and in the range 270–430°C in Atud gold deposit (Harraz, 2002).

(13) Mineralization occurred at different levels within the crust, for example within the range of epithermal-tomesothermal ore deposits in Sukari (Helmy et al., 2004), in the range ~800–1800 m in the El Sid deposit (Harraz, 2000), in the range 330 m–4.5 km in the Atalla deposit (Zoheir et al., 2018b), within the range 2.6–3.1 km in the Um Samra (Shazly et al., 1998), and in the range 2.4–3.6 km in the Um Bakra (Shazly et al., 1998). Gidami gold deposit was formed at a depth around 3 km (Abd El Monsef et al., 2018), and Atud deposit occurred at ~6–11 km (Harraz, 2002).

(14) The Najd faults were important regional structural conduits for magma ascending in the different sites occupied by the IRGDs. It is worth mentioning that the late- to post-orogenic plutonism that hosts the Ad Duwayhi (IRGD) in the Arabian Shield (Doebich et al., 2004) was emplaced during the formation of the northwest-trending Najd strike-slip faults.

8 Intrusion-related Rare Metal Deposits (IRRMDs) in the Eastern Desert

Calc-alkaline/alkaline to peralkaline, highly evolved and halogen-rich granitic rocks are typically associated with rare metal mineralization (e.g., Nb-Ta, Zr-Hf, Sn, W, Be and rare earth elements), and are classified as ‘rare metal granites’ by some authors (e.g., Pollard, 1995, and references therein). In the Eastern Desert of Egypt, rare metal mineralizations were studied thoroughly during a joint Egyptian-Soviet exploration program in 1970, where Sn-Nb-Ta mineralization connected with albitic granite (apogranite) was discovered for the first time at Iglá, Nuweiba, Abu Dabbab, and Humr Waggad (Sabet et al., 1973, 1976d).

Among the Younger Granites in the Eastern Desert of Egypt, and particularly the third phase of these granites,
rare-metal mineralization occurs in many districts such as Sn-Ta-W mineralization in the Abu Dabbab albite granite (Mohamed, 1993, 2013); Sn-Ta-W mineralization in the Nuweibi albite granite (Mohamed, 2013); Sn, Mo, Be and F mineralization in the Humr Akarim and Humrat Mukbid alkali granites and a subordinate roof facies of albite granite (Ali et al., 2012a); Sn-W and Fat Iгла (Sabet et al., 1976a), Mo mineralization in the pink granites of Gabel Qattar (Dardir et al., 1983); F mineralization in the El-Ineigi alkali feldspar granite (Sami et al., 2017); U mineralization in Um Safi (Abouelnaga et al., 2015), etc.

These rare-metal deposits are distinguished by a complex genesis comprising post-magmatic potassium metasomatosis (apogranitization), replacement by pneumatolitic hydrothermal (greisens, stockworks) and hydrothermal (quartz-vein rare metallic type) stages (Sabet et al., 1976a). It is not uncommon to detect the presence of quartz-vein gold occurrences related to the hydrothermal stage of this metallogenic epoch of rare-metal mineralization as indicated by the presence of gold in the quartz veins associated with tin-tungsten-fluorite at Iгла (Sabet et al., 1976a, 1976c).

As previously mentioned, the 610–590 Ma time span, monzogranite and syenogranite plutons in Fawakhir, El Sid and Atalla were emplaced, gold mineralization then occurred at 601 ± 17 Ma in the Fawakhir-El Sid gold district, and at 601 ± 5.5 Ma in the Atalla (Zoheir et al., 2018b, respectively), indicating the presence of a gold mineralization episode at ~600 Ma the Eastern Desert. In contrast, fractionation of volatile-enriched granitic magmas was the most important process in the formation of rare-metal deposits that formed close to 600 Ma at some localities in the Eastern Desert (Kuster, 2009). U, Nb and Ta mineralisation along the Nugrus shear zone was also dated at 608 ± 1 Ma (Lundmark et al., 2012). Most of the Sn, W, Mo, Nb-Ta, REE, Be and F deposits are associated with phase III of the multi-phasic Younger Granite, i.e. G-3 granites of Hussein et al. (1982). This indicates that a distinct metallogenic epoch, comprising both IRGDs and IRRMDs was extremely well-developed at 610–590 Ma or simply at ~600 Ma concurrently with the coeval emplacement of K-rich calc-alkaline and alkaline intrusions in CED and NED of Egypt. This metallogenic epoch was linked with the fourth (610–604 Ma) and fifth (600–590 Ma) magmatic pulses of Lundmark et al. (2012). It is worth mentioning that this metallogenic epoch in the Eastern Desert (i.e. the Nubian Shield) is correlated with the ⁴⁰Ar/³⁹Ar age (597.3 ± 8.2 Ma) for gold-associated white mica hosted in quartz veins traversing the granodiorite intrusion (615 ± 5 Ma) from the Sakhyabarat gold prospect located in the counterpart shield (i.e. the Arabian Shield) (Harbi et al., 2018), which is believed to be affiliated with the IRGDs (Doebich et al., 2004).

This metallogenic epoch at ~600 Ma was contemporaneous with the formation of widespread bimodal dykes, effusion of the Dokhan volcanics, formation of intramontane molasse-type basins and exhumation of gneissic domes.

### 10 Metallogy of the Three Phases of the Younger Granites in Egypt

Given the above, the three phases of the Younger Granites in Egypt have a metallogy of both gold and rare metals in various concentrations. In phase I of the Younger Granites, represented by the Um Rus tonalite-granodiorite (643 ± 9 Ma; Zoheir et al., 2019a), gold mineralization alone exists, with no record for the presence of rare metal mineralization, although Kamel et al. (1992) reported the presence of cassiterite in the auriferous quartz veins and schorlite in the alteration zones of the Um Rus gold deposit. The Hangalia granite (638 ± 5 Ma; Lundmark et al., 2012), representing phase II of the Younger Granite (Jakubiak, 1987), hosts the Hangalia gold deposit and, in addition to gold, the Hangalia veins include native bismuth, ferrocolombite, fergusonite and uraninite (Raslan and Ali, 2010). By the same token, the Fawakhir monzo- syenogranite (598 ± 3 Ma, Andresen et al., 2009) represents phase II of the Gatterian multiphasic Younger Granite and hosts the Fawakhir gold deposit. Besides gold, the Fawakhir quartz veins include wehrlite (a naturally-occurring alloy of bismuth and tellurium), tellurbismuthite (bismuth telluride) and volynskite petzite (silver bismuth telluride) (Osman et al., 2003). Significant correlations between gold and Sn (r = 0.84), as well as gold and Be (r = 0.89) were recorded at 95 percent confidence levels in the Fawakhir-El Sid deposit, this significant correlation leading El Bouseily et al. (1987) to suggest that a Sn-Be mineralization accompanied the Au mineralization.

The third phase of the Younger Granites includes principally rare metal deposits, mostly Sn, W, Mo, Nb-Ta, REE, Be and F deposits as previously mentioned. However, a great number of small deposits and occurrences of gold are linked with this phase in such a way that they occur either immediately in the third phase of the Gattarian granite, as in the Um Samara and Hamrat Ghanam districts, or near them, as in the apogranite massifs of Mueilha, Um Markha and Abu Dabbab (Sabet et al., 1976a). Direct signs of a genetic relationship between the gold mineralization and the metazomatically-altered granites of the third phase is given by the presence of traces of gold in artificial panning samples from the apogranites of Abu Dabbab and Nuweibi (Sabet et al., 1976a).

Disseminations of fine-grained gold in the entire granite stock and/or quartz veins of Sn-W-Ta-U mineralizations, with some concentrations of gold traversing the third phase, are recorded in the Eastern Desert. Typical examples are the occurrence of gold up to 0.5 g/t in

### 9 Relationships between IRGDs and IRRMDs

As previously mentioned, the 610–590 Ma time span, monzogranite and syenogranite plutons in Fawakhir, El Sid and Atalla were emplaced, gold mineralization then occurred at 601 ± 17 Ma in the Fawakhir-El Sid gold district, and at 601 ± 5.5 Ma in the Atalla (Zoheir et al., 2015; Zoheir et al., 2018a, respectively), indicating the presence of a gold mineralization episode at ~600 Ma in the Eastern Desert. In contrast, fractionation of volatile-enriched granitic magmas was the most important process in the formation of rare-metal deposits that formed close to 600 Ma at some localities in the Eastern Desert (Kuster, 2009). U, Nb and Ta mineralisation along the Nugrus shear zone was also dated at 608 ± 1 Ma (Lundmark et al., 2012). Most of the Sn, W, Mo, Nb-Ta, REE, Be and F deposits are associated with phase III of the multi-phasic Younger Granite, i.e. G-3 granites of Hussein et al. (1982). This indicates that a distinct metallogenic epoch, comprising both IRGDs and IRRMDs was extremely well-developed at 610–590 Ma or simply at ~600 Ma concurrently with the coeval emplacement of K-rich calc-alkaline and alkaline intrusions in CED and NED of Egypt. This metallogenic epoch was linked with the fourth (610–604 Ma) and fifth (600–590 Ma) magmatic pulses of Lundmark et al. (2012). It is worth mentioning that this metallogenic epoch in the Eastern Desert (i.e. the Nubian Shield) is correlated with the ⁴⁰Ar/³⁹Ar age (597.3 ± 8.2 Ma) for gold-associated white mica hosted in quartz veins traversing the granodiorite intrusion (615 ± 5 Ma) from

the Sakhyabarat gold prospect located in the counterpart shield (i.e. the Arabian Shield) (Harbi et al., 2018), which is believed to be affiliated with the IRGDs (Doebich et al., 2004).
jasperoid silica veins hosting uranium mineralization (Hussein, 1990), the presence of traces of gold in tantalum-niobium mineralization hosted in apogranite at the Abu Dabbab locality (Sabet et al., 1976c), the presence of gold (0.5–24 ppm) in rare metal-bearing quartz veins at the localities of Um Bisilla and Igla (Sabet et al., 1976c), the presence of gold (0.2 ppm), silver (up to 60 ppm) and antimony (up to 0.06%) in quartz veins carrying wolframite (0.06%–1%) in Abu Kharif (Abd El Nabi and Prokhorov, 1977) and traces of gold (up to 0.2 ppm) in molybdenite-bearing quartz veins in Fatira El Beida (Abd El Nabi et al., 1977).

To sum up, intrusion-related gold deposits and intrusion-related rare metal deposits occur in the Eastern Desert of Egypt, these mineralizations being connected spatially and genetically with the three phases of the Younger Granites, and it seems, in the light of the available geochronological data, that mineralizations commenced at ~630 Ma and reached their apex at ~660 Ma, then diminished and waned over the maturation stage (580–550 Ma).

11 Discussions

The generation an intrusion-related deposit, whether intrusion-related rare metal deposit or an intrusion-related gold deposit, involves some requirements: 1) generation of hydrous silicate magma; 2) presence of Cl and F in the crystallizing magma. 3) a path way that facilitates the passage of the magma along the different levels of the crust, and 4) crystallization of the magma.

11.1 Generation of the magma

As previously mentioned, in the later stages of the collisional events, the Eastern Desert of Egypt underwent a transition at ~635–630 Ma in deformation style from compressional to extensional and a switching from subduction and crustal thickening to delamination and crustal thinning. At ~630 Ma, the mantle lithosphere was removed/delaminated from below the northern ANS, the crustal thinning. At ~630 Ma, the mantle lithosphere was removed/delaminated from below the northern ANS, and the asthenosphere upwelling asthenosphere releasing a steady stream of volatile-rich fluids which locally ‘soaked’ the lower crust and induced the enrichment of fluorine, alkalis, HFSEs and REEs in the crust, then the asthenosphere-derived magma ascended and underplated the soaked lower crust, causing a moderate-degree of partial melting for this crust and the formation of a K-rich calc-alkaline magma, that produced phase I and sub-phases of phase II of the multi-phasic Younger ‘Gattarian’ Granites. Surface uplift of the northern ANS to elevations of >3 km took place due to the previous magmatism, thus promoting rapid erosional unroofing that led to decompression, in turn facilitating the partial melting of the upper mantle and lower soaked crust, producing widespread post-collisional alkaline magmatism at 610 Ma that intraplated the middle and upper crustal levels and formed the highly differentiated calc-alkaline and alkaline granites by subsequent magmatic fractionation processes.

It is to be noted that the coeval emplacement of the highly differentiated calc-alkaline and alkaline magmas at 610–590 Ma explains why most of the IRGDs in Egypt are geochemically metaluminous to weakly peraluminous. However, some of the alkaline granites formed in the time interval 610–590 Ma are assigned to the third phase of the Younger Granites and are mainly peraluminous hosting IRRMDs.

11.2 Presences of Cl and F in the crystallizing magma

Previous studies revealed that the solubility of Au in halogen-free granitic melts is low, typically less than 3 ppm within the temperature range of 900°C to 1250°C and pressures of 6 to 9 kbars (Hoosain, 1999). The presence of Cl in the melt dramatically increases Au solubility by 3 orders of magnitude, Au solubility in a Cl-bearing melts at the temperature/pressure range of 900°C to 1250°C and 6 to 9 kbars, having a maximum value of 1900 ppm (Hoosain, 1999). Au is a highly siderophile and incompatible element in silicate minerals and preferentially remains in the melt. However, silicate melts are not able to accommodate high concentrations of Au, due to a high degree of polymerization (Connors et al., 1993).

On the other hand, the presence of F in silicate melts causes depolymerization, increases rates of cation and volatile diffusion, decreasing melt viscosities and prolonging the duration of magmatic differentiation (Dingwell, 1985, 1989; Dingwell et al., 1985; Webster and Holloway, 1990; Kohn et al., 1991; Schaller et al., 1992; Baker, 1993; Chen et al., 2014). It is worth noting that fluorine is largely dissolved in the magma, even during the late stages of magmatic evolution.

11.3 The transportation of the magma (Najd Fault System)

The Najd Fault System (NFS) is a complex set of left-lateral strike-slip faults and ductile shear zones that strike NW–SE across the Precambrian of Arabia and Egypt. This system is also known in Egypt as the Wadi Hodein-Wadi Kharit shear system (Greiling et al., 1994; Stern, 1994) and Hamrawin (Duwi) shear zone (Makroum, 2017).

This strike-slip system strikes approximately parallel to the orogen over a distance of hundred kilometres. The eastern and western gneissic dome margins are bounded by this sinistral strike-slip shear zones, whereas the northern and southern margins are defined by north- and south-dipping NE-trending normal faults that accommodated exhumation of the gneissic domes (Wallbrecher et al., 1993; Fritz et al., 1996, 2002). These structures are related to ESE–WNW compression with contemporary N–S extension and are accompanied by late-tectonic granitoid emplacement (Fritz et al., 1996; Bregar et al., 2002).

This system was developed during the interval ~620–540 Ma (Stern, 1985), the period of activity being thought to be ~580–530 Ma (Fleck et al., 1980). However, Stacey and Agar (1985) have shown that the activity might have started as early as ~630 Ma as a dextral system and then at about 620 Ma as a sinistral system up to ~530 Ma. Stoees and Camp (1985) suggested that a major left-lateral wrench fault system was active in the interval ~630–550 Ma.

From this data, it appears that the activity of the NFS might have started as early as ~630 Ma, with the NFS
playing multiple roles in the formation of IRGDs in the central part of the Eastern Desert. These roles are summarized here: 1) It acted as a conduit for magma ascending to the middle and near-upper crustal levels (Azer and Farahat, 2011; Sami et al., 2017, 2018; Khalil et al., 2018); 2) It resulted in NW–SE directed extension, which provided depocentres for the accumulation of the post-amalgamation intramontane molasse basins such as the Kareim Basin (Fritz and Messner, 1999; Fritz et al., 2002) and creating weak zones for the intrusion of the late to post-collisional granitoid rocks. This explains the plentiful supply of younger granitoid rocks in the vicinity of the gneissic domes, as well as restriction of IRGDs within the NFS belt. However, exhumed rock types and the interplay between magmatic and tectonic activities vary from gneissic dome to gneissic dome (Fritz et al., 2002). For example in the Meatiq and Hafafit domes, gneissic domes dominate and only a limited amount of late-to post-collisional granitoid rocks are exposed, whereas at the Sibai dome, the area is made up almost entirely of late Pan-African plutons (Fritz et al., 2002).

The southern Eastern Desert, in general, seems to represent a deeper level of exposure than the central Eastern Desert and is less affected by Najd shearing (Hamimi et al., 2019). This explains the rarity of the late to post collisional intrusions and, in turn, the IRGDs in this part of the Eastern Desert. Instead, the major structures in the south are the accretion-induced sutures such as the Allaqi-Heiani Suture and the Onib-Sol Hamed suture (Fig. 7) which host orogenic gold deposits (Zoheir et al., 2019b).

11.4 Crystallization of the magma

In the Eastern Desert, the Younger Granites form composite or multi-phasic plutons. For example, the Deleihimi younger granitoids form a multi-phasic pluton composed largely of late collisional biotite granitoids enclosing granodiorite microgranular enclaves and intruded by leucocratic and muscovite granites (Farahat et al., 2011). Gabal El-Ineigi is a composite younger granite pluton consisting of a porphyritic syenogranite and highly evolved alkali-feldspar granite pertaining to rare metal type fluorite mineralization (Sami et al., 2017). Additionally, the Fawkakhir pluton is composed of a dark grey monzodiorite phase (forming discrete marginal parts of the intrusion) cut by a younger, much more voluminous pink monzo-syenogranite phase (Fowler, 2001). The Um Samra pluton is also a composite pluton with variable composition ranging from monzogranite through syenogranite to alkali feldspar granite with gradational contacts (Ibrahim et al., 2017). Generally speaking, within the multi-phasic plutons, these phases can be readily distinguished based on texture, grain size, mineralogy, geochemistry and field relationships.

All the common ore-forming elements are present in magma in amounts ranging from a few parts per billion to several thousands of parts per million. Gold is traditionally considered to be associated with oxidized intrusions (Ishihara, 1981, 1998), however, the reduced character of some gold-related intrusions had also been recognized (Hart, 2005 and references therein). Rosa (2005) suggested that gold seems to show contrasting behaviours during magmatic evolution according to the $f_{O_2}$ of the melts. In more oxidized conditions, characterized by the presence of magnetite as the main Fe-Ti oxide, gold content in plutonic rocks decreases with increasing differentiation. On the other hand, in more reduced conditions, characterized by the predominance of ilmenite, gold content in plutonic rocks increases with increasing differentiation.

This behaviour of gold towards the two completely different magmas, leads to the question: is gold a compatible or incompatible element? Some authors believe that gold is an incompatible element in silicate minerals (Philpotts, 1990; O’Neill et al., 1995); others believe that gold is a compatible element, as demonstrated by the presence of some disseminations of gold in sulfide minerals, such as arsenopyrite, chalcopyrite and pyrite. Rosa (2005) suggested that Au can be considered as compatible and/or incompatible depending on the oxidation states of the gold. It is known that common oxidation states of gold are $+1$ gold (or aurous compounds) and $+3$ gold (or auric compounds), and it is hypothesized that under more oxidizing conditions, auric gold is present, which is easily incorporated in the crystallizing magnetite, due to its similar size to ferrous and, to a lesser degree ferric iron, where magnetite effectively acts as a sink for gold causing its early removal from the melt (Rosa, 2005). Under more reducing conditions, aurous gold is the only gold cation present, its larger size preventing it from being incorporated into the ilmenite and possibly the magnetite. Therefore, gold behaves as an incompatible element and tends to concentrate in the later fluids, possibly leading to gold mineralization related to highly evolved fluids (Rosa, 2005).

Melt inclusions are small blebs of silicate liquid trapped...
Metal evolution in the composite granitic pluton hosting the Timbarra gold deposit in Australia was tracked by analyzing melt inclusions in quartz samples from seven zones showing the fractionation stages in this composite pluton (Mustard et al., 2006). In this interesting study, the authors presented quantitative microanalyses of Au in granitic silicate melt inclusions using laser ablation inductively coupled plasma mass-spectrometry, showing how Au and other metals (Mo, W, Bi, As, Sb, Cu, Pb, Zn) had become enriched during fractional crystallization in a granite intrusion. The results of the melt inclusion analyses for Mo, W, Bi, As, Sb, Cu, Pb, Zn, and Au from each increasingly fractionated zone of the multi- phasic pluton in Australia, revealed that all metals are enriched in the residual melt, although Sn, W, Mo, As, Sb, and Bi are known to be compatible in minerals such as titanite, ilmenite, and magnetite. This indicates a generally incompatible behavior of the metals during crystal fractionation (Mustard et al., 2006 and references therein). Mo, W, Bi, As, and Sb become more enriched (5–20x) during fractionation compared to the base metals Zn, Pb, and Cu (1–3x). Gold shows a slightly higher enrichment factor (40 x) calculated by assuming an average crustal concentration of Au for 0.003 ppm for the least fractionated stage. Tin shows the highest enrichment during fractionation (300 x) (Mustard et al., 2006).

Mustard et al. (2006) came to the conclusion that Au was enriched during fractionation from a monzogranite to a highly-fractionated alkali-feldspar granite. Similar enrichment behavior for other metals implies that no gold-enriched precursor melt is required and fractional crystallization can enrich the Au concentration to economic levels.

To sum up, crystallization is one of the main controls on the concentration of ore components in magmas, with gold behaving as an incompatible metal and during crystal fractionation, becoming enriched in the residual melt and in the latest stages of the crystallizing magma i.e. in the late hydrothermal stage related to the causative intrusion.

As previously mentioned, a distinct metallogenic epoch of both rare metal and gold was undergoing extreme development concurrent with the emplaced calc-alkaline and alkaline intrusions at ~600 Ma in the CED and NED of Egypt. Generally speaking, during the crystallization of magma, there are at least three main stages: the orthomagmatic stage, the pneumatolitic stage, and the hydrothermal stage. Previous studies carried out on rare-metal mineralization in Egypt revealed that columbite, tantalite and topaz are mainly crystallized as magmatic minerals from the residual interstitial melt at the late orthomagmatic stage at temperatures between 450°C and 550°C (Mohamed, 2013; Emam et al., 2018), some cassiterite also potentially forming in this orthomagmatic stage.

Pneumatolitic processes occur during the final stages of crystallization, where the melt-volatile-rich phase (boron-bearing and fluorine-bearing vapours) escapes at a temperature of 400°C from the cooling silicate magma along joints and fractures, producing greisen selvages along the mineralized quartz veins (Hussein, 1990) with a mineralization assemblage represented by quartz, beryl, topaz, cassiterite, fluorite, and white mica (Mohamed, 2013).

The late hydrothermal stage in intrusion-related rare-metal mineralizations in the Eastern Desert of Egypt took place at temperatures between 200°C and 350°C, being dominated by homogenous H₂O-CO₂-NaCl fluid, the mineralization associated with this stage being represented by quartz veins with cassiterite ± wolframite ± chalcopyrite and fluorite (Mohamed, 2013; Emam et al., 2018).

It is clear that in intrusion-related rare metal deposits such as those occurring in the Eastern Desert, columbite-tantalite and cassiterite disseminations occur within the causative granitic body, crystallizing as magmatic minerals at the orthomagmatic stage, then in the last stages of the crystallizing magma i.e. in the late hydrothermal stage, cassiterite and wolframite ± chalcopyrite ± fluorite are formed at temperatures between 200°C and 350°C.

In light of the results of the studies carried out (Mustard et al., 2006; Mohamed, 2013; Emam et al., 2018), it is here suggested that gold in the IRGDs in the Eastern Desert of Egypt was enriched progressively during crystal fractionation of the magma and finally concentrated in the latest stages of the crystallizing magma, i.e. in the late hydrothermal stage related to the causative intrusion. The three phases of the Younger Granite were derived from magma formed by partial melting of soaked protolith enriched by fluorine, alkalis, HFSEs and REEs, so the auriferous quartz veins in the IRGDs carry other ore minerals, in addition to gold, not occurring in the orogenic gold deposits of Egypt. For example, cassiterite and gold occur in black jasper veins traversing monzogranites-syenogranites to alkali feldspar granites in the Um Samra–Um Bakra district (Ibrahim et al., 2017). Kamel et al. (1992) also reported the presence of cassiterite in the auriferous quartz veins traversing the tonalite-granodiorite hosting the Um Rus gold deposit. Gold-copper-tungsten veins have been recorded as traversing the post-collisional granite in the Abu Garahish gold prospect is recorded (Kleem and Klemm, 1994). Fluorite has been recorded in the Gidami auriferous quartz veins (Abd El Monsef et al., 2018). Bismuth within the range 1–80 ppm is associated with gold in the quartz veins of the Um Samra gold occurrence and in the range 2–100 ppm in the quartz veins of the Um Bakra occurrence (Shazly et al., 1998). Molybdenite is occasionally found in the smoky quartz veins of the Atalla gold deposit (Basta et al., 1996), and in the Gidami auriferous quartz veins (Abd El Monsef et al., 2018). Scheelite was recorded within the mineral constituents of the white quartz veins in the Wadi El Nabsh El Kadim occurrences (Wassef and Boulgatov, 1971), and a Sn–Be mineralization accompanied the Au mineralization in the El Sid gold deposit (El Bouseily et al., 1987). Schorlrite was recorded in the alteration zones of the Um Rus gold deposit (Kamel et al., 1992).
Comparison between the mineral constituents in the auriferous quartz veins in the IRRGDs, and the quartz veins of the late hydrothermal quartz stage in the IRRMDs in the Eastern Desert (Mohamed, 2013; Esm et al., 2018), reveals the following: 1) both took place at temperatures between 200°C and 350°C; 2) both were derived from homogenous H2O-CO2-NaCl fluid; 3) the mineralization associated with the IRRGDs is quartz veins with gold + pyrite+ arsenopyrite + chalcopyrite ± sphalerite ± galena ± cassiterite ± wolframite + fluorite, whereas in the late hydrothermal stage of IRRMDs, mineralization involves quartz veins with cassiterite ± wolframite + chalcopyrite and fluorite. According to Sabet et al. (1976a), the presence of gold-quartz veins associating tin-tungsten-fluorite quartz veins at Iglâ reflects a gold mineralization related to the hydrothermal stage of the metallogenic epoch of rare-metal mineralization.

It is clear that cassiterite, wolframite and fluorite, most commonly acting as incompatible elements are concentrated progressively during crystal fractionation of the magma and finally concentrated in the last stages of the crystallizing magma i.e. in the late hydrothermal stage related to the causative intrusion whether the intrusion is related to phases I and sub-phases of phase II of Younger Granites (causative for IRRGDs) or phase III (causative for IRRMDs).

The variability in the concentration of the ore minerals is governed by: 1) melt composition and magma oxidation state, 2) the temperature and pressure of crystallization, 3) behaviour of the elements such as Au, Mo, W, Bi, As, Sb, Cu, Pb, Zn, etc. during fractional crystallization in the granite intrusion, and in turn, the degree of compatibility or incompatibility of these elements, 4) ore components acquired during magma transit through the crust, 5) abundance or deficiency of Fe-Ti oxides and sulphide minerals that tend to sequester chalcopyrite and siderophile elements, and 6) the concentration of the complexing ligands (e.g., Cl−, HS−, F−) in the magma.

12 Conclusions

We conclude the following from this review:

(1) The Younger Granites, known as ‘Gattarian’ granites in the archives of the Egyptian Geological Survey, are multi-phasic, with three successive phases have been distinguished and mapped separately in the Eastern Desert.

(2) The time around ~630 Ma represents the maximum crustal-mantle thickening and initiation of the delamination process in the Eastern Desert. The transition from late- to post-collisional granites at 610 Ma, along with the coexistence of both calc-alkaline and alkaline magmas at the 610–590 Ma time span was significant from the economical point of view, as indicated by the emplacement of plutons of monzogranite-syenogranite and biotite-alkali granite hosting gold deposits and occurrences in the Fawakhir (598 ± 3 Ma) and Um Had (596 ± 2 Ma) districts.

(3) The presence of an episode of gold mineralization in the Eastern Desert at ~600 Ma (Zoheir et al., 2015, 2018a), and the formation of rare metal mineralization hosted in the granites of the Eastern Desert close to 600 Ma (Kuster, 2009; Lundmark et al., 2012), points to the presence of a distinct metallogenic epoch for both rare metals and gold contemporaneous with the coevally-emplaced calc-alkaline and alkaline intrusions at ~600 Ma in the CED and NED of Egypt. This metallogenic epoch at ~600 Ma was concurrent with the formation of widespread bimodal dykes, the effusion of the Dokhan volcanics, the formation of intramontane molasse-type basins, and exhumation of gneissic domes.

(4) Crystallization is one of the main controls on the concentration of ore components in magmas, with gold behaving as an incompatible metal, becoming enriched and during crystal fractionation in the residual melt and finally in the last stages of the crystallizing magma i.e. in the late hydrothermal stage related to the causative intrusion. As the three phases of the Younger Granite are derived from magma formed by partial melting of ‘soaked’ protolith enriched with fluorine, alkalis, HFSEs and REEs, the auriferous quartz veins in the IRRGDs carry other ore minerals, besides gold that do not occur in the orogenic gold deposits of Egypt, e.g. cassiterite, tungsten, fluorite, molybdenite and scheelite.

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