

# Geology of Rare Metals in Egypt- A review

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Received 12 January 2021

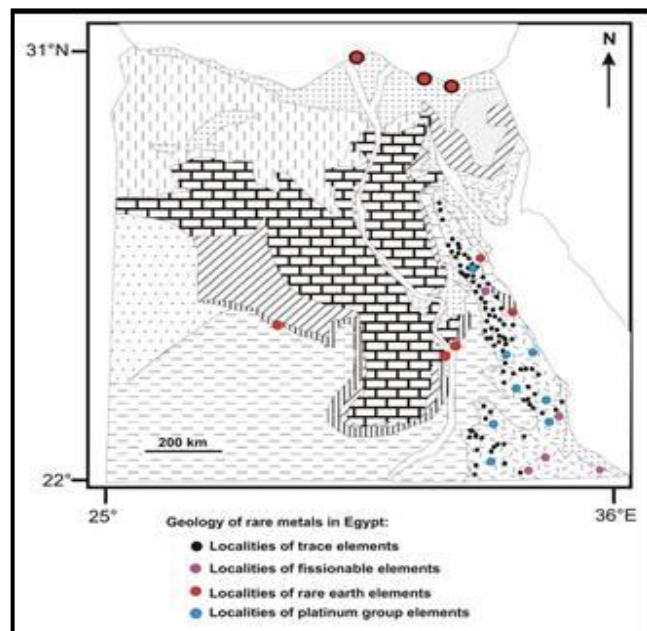
Revised 9 February 2021

Accepted for publication 10 February 2021

Published online: 30 June 2021

## Abstract

The term “rare metals” refers in this work to metals with a low availability in natural. Based on their chemistry, rare metals were classified into; 1) rare earth elements (La-Lu), 2) trace elements (Nb, Ta, Mo, Cu, Ni, Co, Sn, W, V), 3) noble elements (Au, Ag, and PGE) and 4) fissionable elements (U and Th). In Egypt, rare earth elements occur in the phosphorites, monazite and granites. Trace elements occur in three associations; a) elements in granites and albite granites such as Nb, Ta, Sn, Mo, and W, b) elements associate mafic rocks and ophiolites include Cu, Ni, and Co, and c) V in the black shales. 95 Au localities were reported mainly as vein-type mineralization in the Eastern Desert. PGE are confined to three associations including mafic and ultramafic rocks, chromite and black shales as sulfides, alloys, and organometallic compounds, respectively. Uranium occurs in granites of the Eastern Desert. Thorium was reported at the Um Ara area at the Eastern Desert and in the monazite from the black sands. Although rare metals are quite common in Egypt, processing and beneficiations of the rare metals-bearing rocks did not reflect the abundance and the economic significance of these metals.



**Keywords:** Rare Earth Elements; Trace Elements; Noble Elements; Fissionable Elements; Egypt

## 1. Introduction

The term “rare metals” is not strictly defined [1,2,3]. According to Simandl [3], it refers mainly to

uncommon, nonferrous metals used in small quantities, typically < 150 000 tones/year, or derived from

geographically restricted areas. Behrendt et al. [2] suggested three definitions for the rare metals. 1) Rare metals are the expensive metals or whose price has increased intensely. 2) Rare metals are metals with a low present availability. 3) Rare metals are metals which are only mined in a few countries. They analyzed several arguments for the “rarity” of metals using the following measures:

- Price: metal prices of almost 500 USD per kg;
- Price increase: an increase in the price of metals in more than 100 % in 2001 to 2004- Shortage of reserves: reserves lasting less than 25 years, based on production statistics in 2004;
- Concentration in quantity and value chain or high concentration of reserves.

In Japan, the term rare is frequently used to refer to the 47 metal elements, based on the definition established by the Ministry of Economic, Trade and Industry. There are a total of 89 elements in the natural world and over half of these elements are rare metals [2]. In this paper, definition 2 of Behrendt et al. [2] that rare metals are metals with a low availability, will be used. Based on their chemical properties and association, rare metals are classified in this work into four groups (Fig. 1) including: (1) rare earth elements

(REE) of the 14 lanthanide elements from La to Lu as they behave similarly and occur as a group in rocks and minerals, (2) trace elements including elements occur in relatively low concentrations (ppm) and usually present in rocks and minerals as associations include a number of elements, (3) noble elements include precious elements particularly platinum group elements (PGE) and gold, and (4) fissionable elements include radioactive elements particularly U and Th. The applications, markets, characterizations, and occurrences in Egypt of these metals will also follow this classification scheme.

Due to their vast industrial applications particularly in electronic and automobile industries, the need of rare metals has amplified intensely in the last few decades [4,5]. Thus, finding additional resources of the rare metals is vital to bridge the increasing gap between production and needs. This work shows a critical review of the potential occurrences of rare metals in Egypt that can be an important source of these metals to the regional and global markets. The review focuses on the localities, concentrations (geochemistry), the modes of occurrences (mineralogy), and origin of the rare metals in Egypt.

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	G18	
P1	H																	He	
P2	Li	Be											B	C	N	O	F	Ne	
P3	Na	Mg											Al	Si	P	S	Cl	Ar	
P4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
P5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Au	Cd	In	Sn	Sb	Te	I	Xe	
P6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Ag	Hg	Tl	Pb	Bi	Po	At	Rn	
P7	Fr	Ra	Ac																
Lanthanides	La	Ce	Pr	Nd	Pm	Sm	Eu					Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinides	Ac	Th	Pa	U															

Rare earth elements    
  Trace elements    
  Noble elements    
  Fissionable elements

**Fig. 1** Classification of rare metals into four groups based on their chemical properties.

## 2. Occurrences of rare metals in Egypt

This review will follow the abovementioned classification of rare metals into rare earth elements, trace, noble, and fissionable elements.

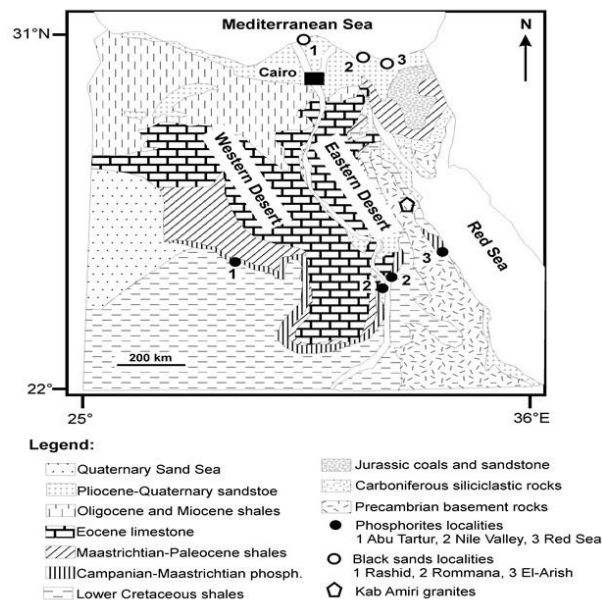
### 2.1. Rare earth elements (REE)

Three potential occurrences of REE-bearing rocks in Egypt include phosphorites, black sands, and granites.

The occurrences of these rocks in economic scale are shown in Figure 2.

#### 2.1.1. Phosphorites

Phosphorite deposits that belong to the Duwi Formation represent one of the major deposits of economic importance in Egypt. Phosphatic deposits comprise a part of the widespread late Cretaceous-Eocene Tethyan phosphogenesis. Huge quantities of phosphorites (~30 x 10<sup>9</sup> T) were accumulated in this



**Fig. 2** Geological map of Egypt showing the potential occurrences of REE-bearing rocks (modified from [6]).

phosphogenic province, including  $7 \times 10^9$  T deposited in the Middle East area [7]. The phosphorite resources in Egypt only are more than 3 billion metric tons (Notholt, 1985). They are exploited from three regions in the Red Sea, Nile Valley, and Abu-Tartur areas in what is called “the phosphorite belt” (Fig. 2).

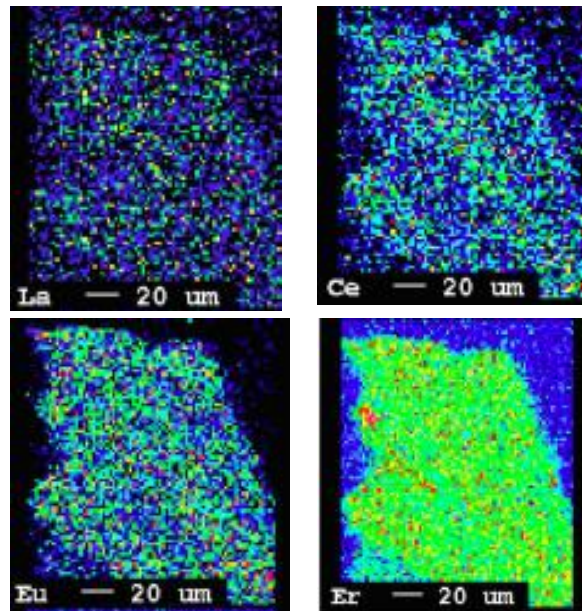
Abu Tartur area is considered as the highest phosphate reserve in Egypt, the reserve is estimated to be about 2 billion metric tons [8]. Apatite ( $\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$ ) is the major constituent of these phosphorites beside non-phosphatic constituents such as detrital quartz, glauconite, pyrite, dolomite, calcite, gypsum, and anhydrite [9,10].

Rare earth elements distributions in the Red Sea, Nile Valley, and Abu-Tartur phosphorites are displayed in Table 1 [11]. The Abu-Tartur deposit exhibit higher rare earth elements concentrations (average 685 ppm) relative to the Red Sea (average 212 ppm) and Nile Valley (average 165 ppm) phosphorites. Awadalla [12] reported concentrations of REE in the Abu Tartur phosphorites ranging from 518 to 1011 ppm. EPMA mapping of the apatite grains showed homogeneous distributed of REE in the grains (Fig. 3) [12] suggesting the occurrence of these elements in the structure of apatite replacing Ca. This was also confirmed by the general positive correlations between  $\Sigma\text{REE}$  and the  $\text{P}_2\text{O}_5$  contents (Fig. 4) [12]. According to Baioumy [11], the high REE concentrations in the Abu Tartur

phosphorites relative to other areas, suggested post-depositional alterations of the REEs contents and patterns during diagenesis due to the deposition of these deposits in different depositional environments.

### 2.1.2. Black sands

Black sand deposits of Egypt are beach placers accumulated from the Nile River during flood seasons arrive the Mediterranean Sea at river mouth [13]. Figure 2 displays the distribution of the black sands in Egypt alongside the Mediterranean Sea coast from Rafah East to Alexandria West. Black sands comprise several economic minerals such as magnetite, ilmenite, hematite, zircon, rutile, monazite and garnet. The reserves of economic minerals at Rashid area are shown in Table 2 [13].



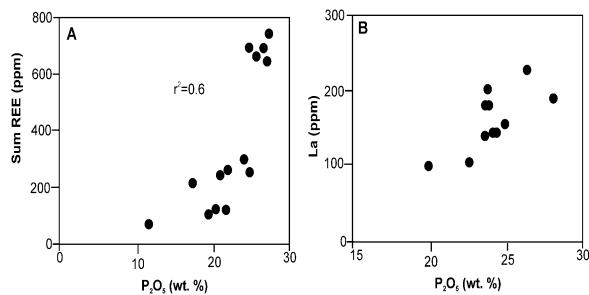
**Fig. 3** EPMA elemental mapping of the apatite grains from the Abu Tartur area showing the homogeneous distributions of REE in the apatite grains [12].

At Rommana and Al Arish areas that cover an area of  $18 \text{ km}^2$ , the proved reserves of black sands calculated to a depth of 1 m are around 88 million tons, while the proved reserves to a depth of 10 m are estimated by 3 million tons [14]. REE occur in the black sands mainly in the monazite ( $(\text{Ce},\text{La},\text{Nd},\text{Th})\text{PO}_4$ ). Although, the black sands in Egypt are quite common and have economic importance and can be considered as important source of REE, no much information available about the concentrations of REE in the bulk

samples and/or in the separated monazite from these black sands.

**Table 1.** Average REE concentrations (ppm) in the phosphorites, Egypt (modified from [11]).

	Red Sea	Nile Valley	Abu Tartur
La	44.5	39.5	156.6
Ce	71.6	53.4	164.1
Pr	10.7	7.5	36
Nd	43	31.5	154.4
Sm	8.2	6.2	31.4
Eu	2.2	1.7	8.9
Gd	9	6.9	34.9
Tb	1.2	1	5.4
Dy	9	6.6	33.2
Ho	1.9	1.7	7.5
Er	5.5	4.6	21.3
Tm	0.7	0.6	2.9
Yb	4.5	4.1	18.2
Lu	0.8	0.7	2.9
ΣREEs	212.8	165.6	684.6



**Fig. 4** A) General positive correlation between  $P_2O_5$  and  $\Sigma REE$  in the Egyptian phosphorites (data from [11]), B) positive correlation between  $P_2O_5$  and La in Abu Tartur deposits (data from [12]).

#### 4.1.3. Granites

Granites are widely distributed in the Eastern desert and Sinai as a major constituent of the Basement Rocks in these areas. These granites can be a potential source of REEs. At the Kab Amiri area, which is situated nearby the Qena-Safaga Road (Fig. 2), two radioactive anomalies have been described in the Kab Amiri monzogranite: one in the silica veinlets and the other in the pegmatites. The pegmatites are made of quartz cores bounded by alkali feldspar [15,16,17,18,19]. The pegmatites show exceptionally high REE

concentrations The distributions of REE of Kab Amiri deposits in different grain sizes are shown in Table 3.

**Table 2.** Reserves of economic minerals in the Rashid East (data from [13])

Mineral	Reserves (1000 tons)
Ilmenite	2087
Magnetite	1437
Hematite	214
Sulphides	86
Zircon	81
Garnet	72
Monazite	31
Rutile	29

**Table 3.** Distributions of REE of Kab Amiri deposits in various grain sizes (data from [15]).

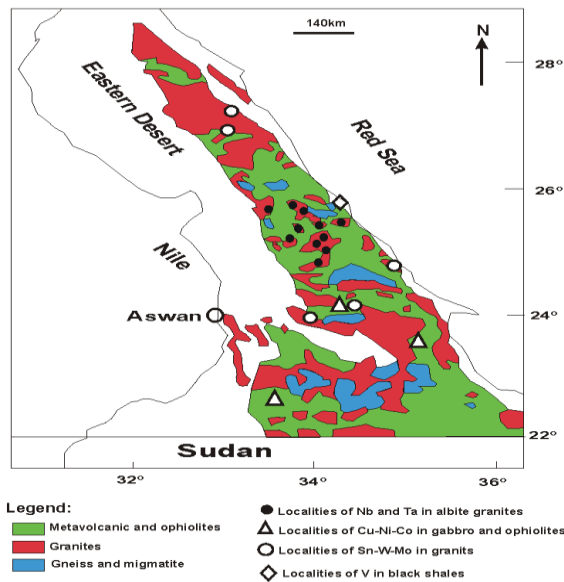
Grain Size ( $\mu m$ )	Weight (%)	REE <sub>2</sub> O <sub>3</sub> (%)
-500	8.2	14.2
-420	6.6	10.7
-297	6.1	9.1
-250	10.6	14.6
-125	17.2	15.8
-74	51.3	35.6

## 2.2. Trace elements

Trace elements in Egypt are quite common and in many cases they occur in association of more than one metal. Figure 5 shows the localities of trace elements in Egypt mainly in the granites and mafic igneous rocks in the Eastern Desert [20].

### 2.2.1. Niobium-Tantalum

In Egypt, niobium and tantalum mineralization occurs in the hard rock deposits and their associated placers in the Precambrian basement rocks of the South Eastern Desert in what is called albite granite. Most of the known occurrences are south of 26° N latitude and east of 34° E longitudes particularly in Abu Dabab, Nuweibe, Abu Rashid, Um Naqat and Zabara areas (Fig. 5) [21,22]. According to Helba, et al. [21], Ta contents in the whole rock range between 63 and 155 ppm, while Nb contents range between 61 and 87 ppm. Table 4 summarizes the Ta-Nb ores in these localities based on the Gippsland Co. reports [23,24].



**Fig. 5** Basement complex in the Eastern Desert showing the potential occurrences of trace elements-bearing rocks (modified from [20]).

**Table 4.** The Ta-Nb ores in the Eastern Desert (data from [23,24]).

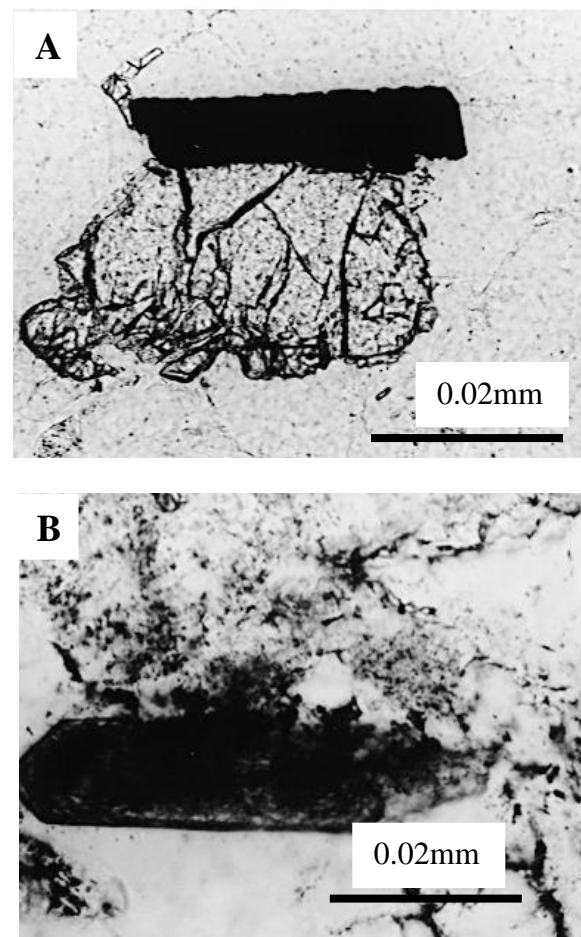
Location	Reserves (million tons)	Average concentrations of Nb and Ta
Abu Dabbab	40	0.27 wt. % Ta <sub>2</sub> O <sub>5</sub>
		0.020 wt.% Nb <sub>2</sub> O <sub>5</sub>
Nuweibi	115	0.017 wt. % Ta <sub>2</sub> O <sub>5</sub>
		0.015 wt. % Nb <sub>2</sub> O <sub>5</sub>
Um Naggat	25	0.022 wt. % Ta <sub>2</sub> O <sub>5</sub>
		0.20 wt. % Nb <sub>2</sub> O <sub>5</sub>
Abu Rashid	Not Calculated	0.033 wt. % Ta <sub>2</sub> O <sub>5</sub>
		0.30 wt. % Nb <sub>2</sub> O <sub>5</sub>

Tantalite-columbite is the major ore mineral in these areas [21]. Other Ta-Nb- Sn-bearing phases recognized in the SEM-EDS analysis containing ixiolite having up to 11 wt. % SnO<sub>2</sub>, stibiotantalite with Sb<sub>2</sub>O<sub>3</sub> up to 6 wt. %, cassiterite and microlite. Tantalite-columbite occurs as subhedral to euhedral, fine-grained (0.05-0.2 mm) bladed crystals in two major generations: 1) as inclusions in muscovite (usually associated with zircon and iron oxides) in quartz phenocrysts (Fig. 6A), and in beryl and topaz crystals; 2) as disseminated grains in the matrix constituents in both western and eastern

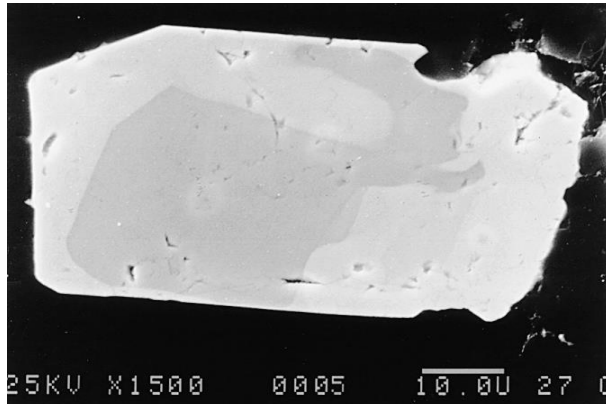
areas. Zircon (Hf-, Th-, U-rich) has been also detected in columbite-tantalite (Fig. 6B).

Under SEM tantalite-columbite commonly display zoning textures, where rims show constantly higher Ta than the cores (Ta-rich borders look brighter in the SEM images) (Fig. 7) [21]. According to Abdalla [21], Nb<sub>2</sub>O<sub>5</sub> concentrations in the Columbite-tantalite mineral grains range between 17 and 76 wt. %, while Ta<sub>2</sub>O<sub>5</sub> concentrations vary from 0.7 to 63 wt. %.

At the Kab Amiri area, Central Eastern Desert, El-Hussaini et al., [15] reported high concentrations of Nb and Ta in the monso granite (Table 5).



**Fig. 6** A) Photomicrographs of tantalite-columbite grain (black) and garnet (high relief, grey) in quartz. (B) Prismatic zircon with partly metamict, cloudy core [21].



**Fig. 7** SEM-photomicrograph of a discontinuously zoned tantalite-columbite crystal from the Nuweibi granite. The dark core (Ta-poor) and overgrowth of brighter Ta-rich parts [21].

El-Kammar et al. [25] considered the granites at G. Gattar as mineralized granites with a relative enrichment of Nb (average of 40 ppm). Carbonatite of the El Mansouri is characterized abnormal Nb (up to 3 wt. % Nb<sub>2</sub>O<sub>5</sub>) as niocalite (Ca<sub>4</sub>NbSi<sub>2</sub>O<sub>10</sub>(O,F)) [26,27]. Anomalous concentrations of Nb (300 ppm) were reported in the carbonatites of Tarbtie South and El Naga [28]. Feldspathized nepheline syenites in El Naga, Nigrub, El Fogani, and Abu Khrug areas are associated with anomalous concentrations of Nb (1300-3000 ppm) [28].

### 2.2.2. Copper-Nickel-Cobalt

Copper-nickel-cobalt sulfide deposits occur in two assemblies in the mafic-ultramafic association in the gabbro members of the ophiolite sequences and in the layered intrusions. The two types occur in Egypt at Abu Swayel and El Geneina areas for the gabbro and Gabbro Akarem for the layered intrusions [29,28,30]. At Abu Swayel area, the ore body include both massive and dispersed mineralization presented in a lens-like body of amphibolite, 30 m wide and 500 m long [31]. The ore minerals contain pyrite, pyrrhotite, cubanite and ilmenite, chalcopyrite, pentlandite, bravoite, violarite, brochianite, malachite and chacanthite (Fig. 8A). Ore reserve have been estimated at 85,000 tons comprising 2.8 wt. % Cu, 1.53 wt. % Ni with minor quantities of Co. At El Geneina, malachite and gamierite-stained gossan occur in mafic-ultramafic rocks that include peridotite, pyroxenite and gabbros. Ore minerals are represented mostly by pyrite,

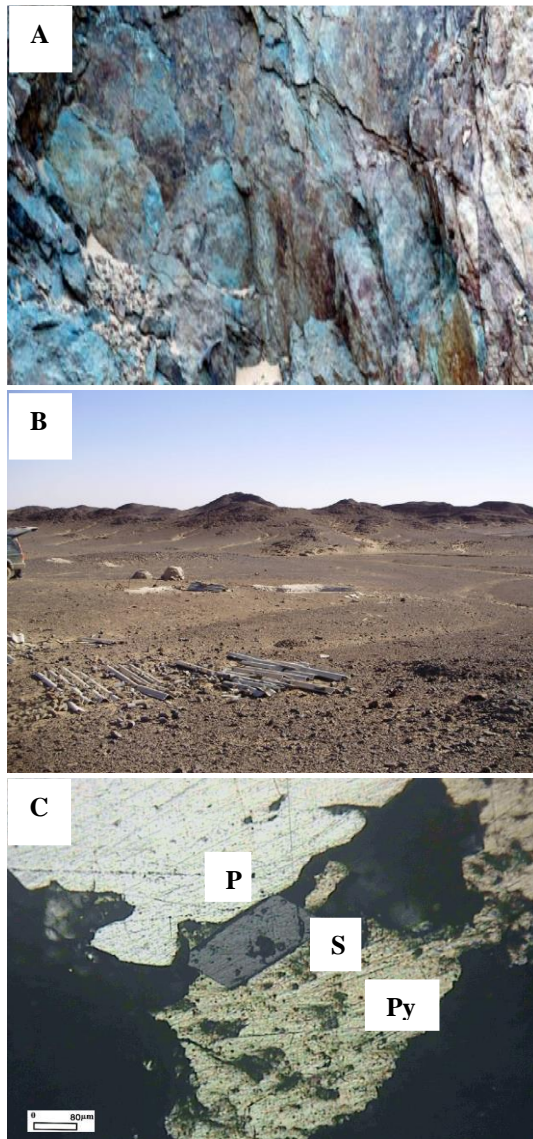
pyrrhotite, chalcopyrite, and pentlandite. Core assay indicated 0.17 wt. % Cu and 0.38 wt. % Ni [28]. At Gabbro Akarem area, disseminated and massive Cu-Ni sulfide mineralization occur within a massive peridotite, norite and melanorite (Fig. 8B and C). Reserve assessed at 700,000 tons of mineralized peridotite as a grade of 0.95 wt. % with Ni and Cu, of which 270,000 tons of grade 1.18 wt. % Ni+Cu [28]. At St John's Island, Red Sea, Ni-bearing veins occur as garnierite-bearing veins extend for about 50 m with a width varying from 0.6 to 2 m with a Ni content of 5 to 9 wt. % [28,32].

**Table 5.** Distributions of Nb and Ta at Kab Amiri ore mineral in different grain sizes (data from [15]).

Grain Size (µm)	Weight (%)	Nb <sub>2</sub> O <sub>5</sub> (%)	Ta <sub>2</sub> O <sub>5</sub> (%)
-500	8.2	10.6	7.9
-420	6.6	8.4	6.4
-297	6.1	8.9	6.2
-250	10.6	8.7	13.2
-125	17.2	15.2	19.0
-74	51.3	48.2	47.4

### 2.2.3. Tin-Tungsten-Molybdenum

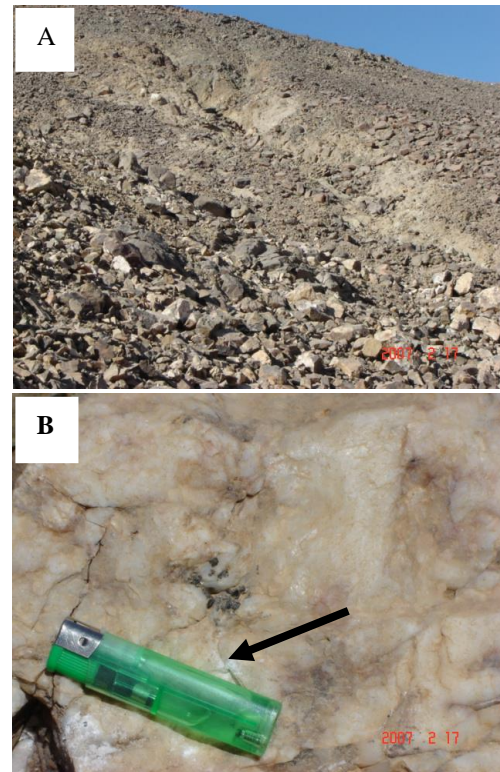
Tin-Tungsten-Molybdenum mineralization has been categorized by Hussein [28] as deposits related to granites. Igla deposit is an example of the Sn-W ores nearby Mersa Alam area (Fig. 9). Molybdenum mineralization presents as vein-type and disseminated at Abu Marwa, Gabal Gattar, Abu Harba, Homer Akarm and Um Disi areas [28]. Molybdenite-bearing quartz veins which cut through the 'Pink granite' distributed in the NED in six localities; Gabal Gattar, AbuHarba, Wadi Dib, Abu Marwa, Umm Disi, and Homret Akarem [33,34] with an average ore grade 0.031 Mo, and the reserves at about 8,000,000 tons [35]. W-bearing minerals generally associates with Sn-bearing minerals in Igla and Muelha areas where in the Igla area, Sn is up to 0.5 % and W up to 0.06 wt. %. Tin presents as vein-type and disseminated in Muelha, Abu Dabbab, Fatira, Abu Kharif, Nuweibi and Abu Hammad areas with geological reserves have been calculated by Anwar et al. [36] as 245000 tons Sn.



**Fig. 8** (A) Photograph showing mineralized peridotite stained with malachite, Abu Swayel area. (B) Photograph showing mineralized peridotite in the Gabbro Akarem area. (C) Photomicrograph showing pyrrhotite (Py), pentlandite (P) and sphalerite (S) in the mineralized peridotite [30].

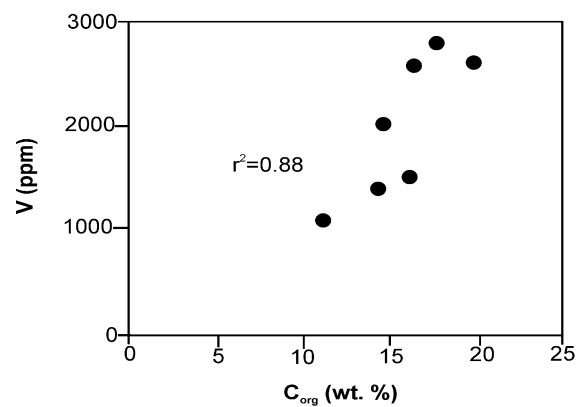
#### 2.2.4. Vanadium

According to Baioumy and Ismael [37], black shales intercalated with the phosphorite deposits in the Red Sea area show considerably high vanadium contents (1056-2800 ppm).



**Fig. 9** A) Field photograph showing granite rocks at the Iгла area. B) Cassiterite grains inside the quartz veins (arrows).

The vanadium contents (Table 6) exhibit positive correlation with the total organic carbon (TOC) in these shales (Fig. 10) suggesting the occurrence of the majority of the V in the organic fraction, probably as organometallic component.



**Fig. 10** Positive correlation between V and total organic carbon (TOC) in the black shales (data from [37]).

**Table 6.** Distribution of V in the black shales from different phosphorite mines, Red Sea area (data from [37]).

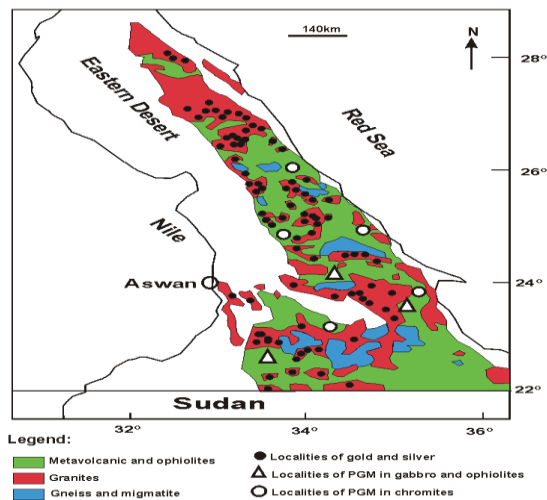
Phosphorite mine	V (ppm)
Galal	2600
Islam	1056
Younos	2800
Water Flow	2350
Tondob	1270

### 2.3. Noble elements

Noble elements in Egypt including Au, Ag and PGE occur in many localities mainly in the basement complex of the Eastern Desert (Fig. 11).

#### 2.3.1. Gold-Silver

Gold is reported in Egypt in more than 95 localities, majority of them have been mined during Pharaonic period [38]. Botros [38] suggested a three-fold classification of gold mineralizations in Egypt related to the tectonic-magmatic development of the Nubian Shield. These include strata-bound, non-strata-bound and placer deposits. Strata-bound gold deposits were

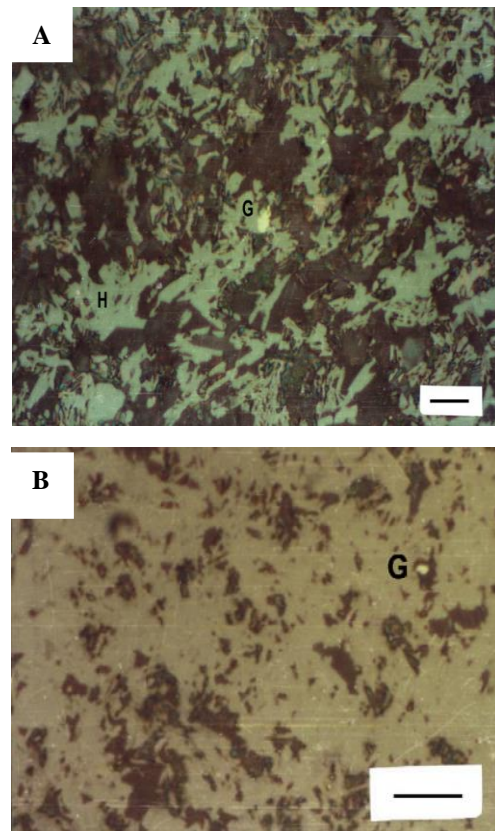


**Fig. 11** Geological map of the basement complex in the Eastern Desert showing the potential occurrences of noble elements-bearing rocks (modified from [20])

further divided into three categories: gold-bearing Algoma-type Banded Iron Formation, gold-bearing volcanogenic massive sulphide and gold-bearing

tuffaceous sediments deposits. The non-strata-bound deposits are subdivided into two major types: vein-type mineralization presented in a widespread range of rocks and disseminated-type mineralization held in hydrothermally altered rocks (alteration zones). Placer deposits have been divided into lithified and modern placers. Gold-bearing Algoma-type Banded Iron Formation was found at Abu Marawat gold [39,40] and Um Nar areas [41]. Gold contents reach up to 2.15 ppm in the formation [39] bounded in the flaky hematite (Fig. 12A) and/or as fine inclusions in the magnetite (Fig. 12B).

Gold-bearing tuffaceous sediments are restricted in regions where volcanic and volcanoclastic rocks are closely intercalated with each other. The gold contents in the auriferous tuffaceous sediments is up to 11.62 ppm in Abu Marawat region [39].



**Fig. 12** A) Photomicrograph of gold grains (G) bounded in the hematic flake (H). B) gold speck (G) enclosed in the Fe-bearing minerals at Abu Marawat area [39].



Volcanic hosted massive sulphide (VHMS) rocks in the Eastern Desert are reported in Helgit, Um Samuki, Maakal, Abu Gurdi, Darhib, El Atshan and Egat areas. Two different spatial and mineralogical associations of gold deposits are recorded in the volcanogenic massive sulphides and their alteration zones (the keel zone) in the Eastern Desert [38]: (1) Gold-silver-zinc association: In this association, gold content are very low (0.3-0.4 ppm) and silver is high, averaging 109 ppm in the Um Samuki VHMS deposit. 2) Gold-copper association:

This association classically presents in alteration zone of the footwall rock (the keel zone) and the basal parts of the massive sulphide deposit. Gold contents reach up to 5.5 ppm with average of 1 ppm. Silver is very low, typically ranges from 4 to 10 ppm. Vein-type gold deposit constituted the core target for gold deposits since ancient ages, where ancient Egyptians mined gold from these veins in underground mines and open-pits. Table 7 summarizes the features of some vein-type gold deposits in Egypt.

**Table 7.** Some vein-type gold mineralization in the Eastern Desert, Egypt (data from [42,40,43]).

Area	Host rocks	Au content
Abu Marawat	Volcano-sedimentary rocks intercalated with diorite-tonalite	1.37-73.48 g/t (average 6.9 g/t)
Erediya	Tonalite-granodiorite	13.2-29.76 g/t
Dungash	Metavolcanic and metapyroclastic Rocks	Average 3.87 g/t
Umm Ud	Metaandesite, metabasalt and their tuffs intercalated with schistose diorites. Both are intruded by quartz veinlers and veins	2-15 g/t (average 3 g/t)
Umm Egat	Chistosed volcano-sedimentary deposits, tonalite	0.3-40 g/t
Umm Garaiart	Metaandesitic tuffs	7.75-155.5 g/t
Betam	Schistosed metasediments intercalated with tonalite-granodiorite	2.0-11.07 g/t

The Barramiya gold is one of the important gold deposits in central Eastern Desert. It locates in midway

between Marsa Alam on the Red Sea coast and Idfu on the Nile bank. The deposit is restricted to gold-bearing quartz veins and neighboring alteration zone. Host rocks are mostly ophiolitic melange in which serpentinite in the western side is transformed autometasomatically into talc-carbonate in the eastern and central sides. Average thickness of the quartz vein is about 1m and spreads for approximately 800 m. The alteration zone around the vein is approximately 6 m thick, and composes of intensively altered graphite and tremolite-actinolite schists with ferruginous, sercitization and kaolinization. Listweanite was formed as bands and lenses as a result of amalgamation of silica and carbonate with gold-bearing spots. Average gold content in the quartz vein ranges between 1.59 and 2.74 g/t with total reserve of 30 tons of gold [44]. The most significant recent gold mines in Egypt are: El Sukary area (Centamine Limited, Pharaoh gold mine) and Hamash area (Hamash Company) (Table 8). Recently, gold has been discovered at Uwaynat, G. Nazar and G. Kamel areas. The gold content in these areas is up to 14 g/t [45].

Most placer gold deposits are close to the auriferous quartz veins as a result of arid and hot climate of the Egyptian deserts resulted in physical weathering. Two major categories of placer gold have formed in Egypt, the modern placers and lithified placers [39]. Recent placers are divided to beach and alluvial placers.

**Table 8.** Recent active gold mine in Egypt, El Sukari and Hamash regions (data from [46]).

Area	Grade g/t	Gold content (M oz.)
El Sukari	1.42	2.94
Hamash	Um Tondob	0.8
	Ara	1.5
	Hamash old mine	2-4
	Abu Tarda	1.5-5

The major accumulation of gold in a mechanically dispersed form in the wadis of the Eastern Desert favors the collection of alluvial placers. Insignificant amounts of gold documented in some Egyptian black beach sands in beach placers on the Mediterranean Sea. Lithified placers occur in the conglomerate at the lower part of the Upper Proterozoic molasse deposits of the Hammamat unit and/or the basal part of the Upper

Cretaceous Nubian Formation that superimposes the Precambrian basement rocks [39].

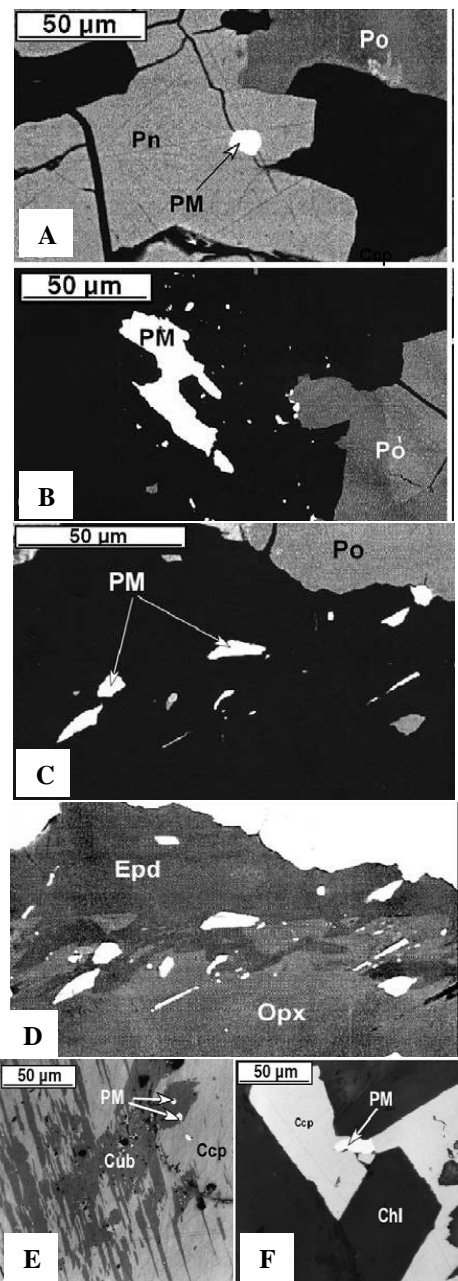
### 2.3.2. Platinum group elements (PGE)

PGE are usually associated with mafic-ultramafic rocks of ophiolite and some layered intrusions or concentrically-zoned mafic ultramafics (gabbro Akarem, Genina Gharbia, Abu Swyil). At the Akarem area, the mafic-ultramafic complex contains layered and peridotite gabbroic. The primary sulfide minerals in these rocks are chalcopyrite, pyrrhotite, cubanite and pentlandite that show disseminated, net and massive textures in the olivine-rich ultramafic host rocks. Secondary minerals include violarite, monoclinic, pyrite, pyrrhotite, magnetite, millerite and mackinawite. Platinum (< 2 ppb) is determined in these sulfide minerals, also far below bulk levels (20-330 ppb). Coarse-grained pyrrhotite contains more Rh (20-120 ppb, average 60 ppb) than bulk rock (average 20 ppb) and other main sulfide minerals. Sulfides and bulk samples have much less Ir (a few ppb) than coarse pyrrhotite (30-100 ppb, average 60 ppb). Coarse-grained pentlandite contains the highest Pd concentrations, up to 1030 ppb [4].

Electron microprobe (EPMA) analysis of the merenskyite-melonite series, Eastern Desert designated that range of the Pd concentrations are 12.6-22.9, 6.5-15.5, and 10.3-24.2 wt. % in the Gabbro Akarem, Genina Gharbia, and Abu Swayel areas of the Eastern Desert, respectively [29]. The Pd-bearing minerals; the melonite group minerals, present at the interface between primary and secondary silicates, along crack in pentlandite, in secondary silicates in contact with pyrrhotite, held in cubanite lamellae in chalcopyrite, and at the boundary of chalcopyrite in a chlorite matrix (Fig. 13) [29].

PGE mineralization was also described in the podiform chromites from the late Proterozoic Pan-African ophiolites in the Eastern Desert. The occurrences of platinum-group minerals (PGM) in the southern Eastern Desert (e.g. Abu Dahr, Abu Syeil, Belmhandite, Arais, and Um-Thagr areas) and central Eastern Desert (e.g. Wadi El-Zarka, Wadi El-Lawi, Um-Huitate, Wadi Bezah, Gebel El-Rubshi and Barramiya areas) chromitites are reasonably distinguishable; they are mostly Os-Ir alloy in the former (Fig. 14 A-C), and sulfides (Os-rich laurite) in the latter (Fig. 14 D-E).

Arsenides and sulfarsenides are also found in subordinate quantities in both chromites [47].

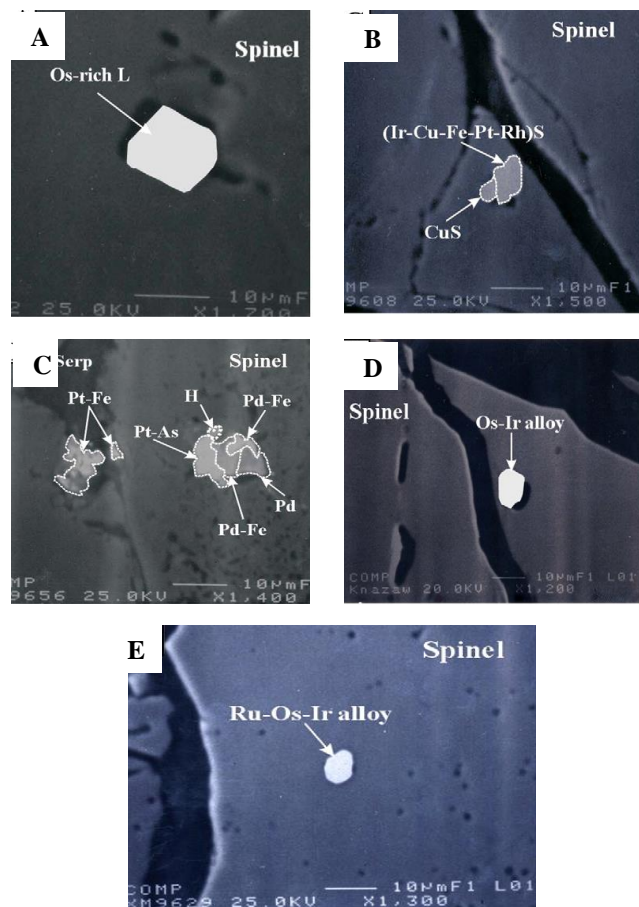


**Fig. 13** BSE images of PGE-bearing minerals from Abu Swayel and Genina Gharbia areas. A) Pd-Bi melonite (PM) along cleavage in pentlandite (Pn). B) Pd-Bi melonite (PM) and other tellurides (small white grains) in secondary silicates (black) in contact with pyrrhotite. C) at the contact between orthopyroxene (Opx) and secondary epidote (Epd) illustrated in (D). E) Pd-Bi melonite (PM) presented in cubanite (Cub) lamellae in chalcopyrite (Ccp). F) Pd-Bi melonite (PM) at the boundary of chalcopyrite in a chlorite (Chl) matrix [29].

Table 9 summarizes the EPMA analyses of PGE-bearing phases in the southern and central Eastern Desert chromites [47]. Table 9 shows selected microprobe analyses of PGE-bearing phases (Wt. %) in the southern and central Eastern Desert chromites of Egypt [47].

### 2.4. Fissionable elements

Fissionable elements in Egypt including U and Th occur in several localities mainly in the basement complex of the Eastern Desert (Fig. 15).



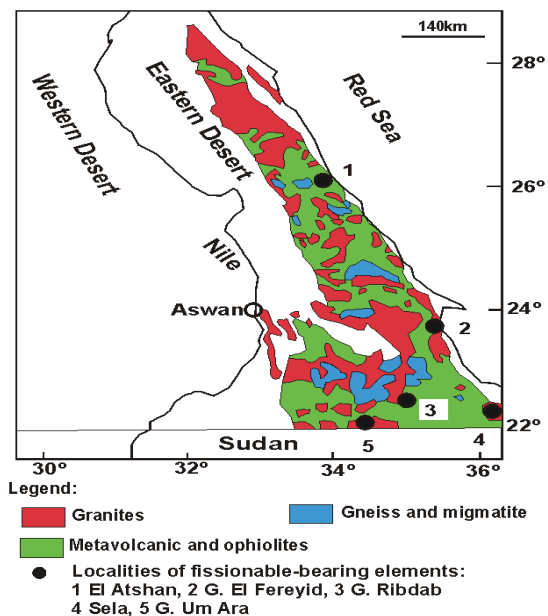
**Fig. 14** BSE images of PGM in the chromites. A) euhedral Os-rich laurite crystals in chromian spinel. B) (Ir-Cu-Fe-Pt-Rh)S combined with CuS in chromian spinel. C) Composite PGM crystals having Pt-Fe alloy, Pd-Fe alloy, sperrylite (Pt-As), native Pd and hollingworthite (H) in chromian spinel. D) euhedral Os-Ir alloy in fresh chromian spinel from Belmhandite. E) Ru-Os-Ir alloy in fresh chromian spinel [47].

### 2.3.4.1. Uranium

Dawood [48] reported a secondary uranium deposit at Um Ara region, Eastern Desert with U concentration varies from 0.15 to 20.3 wt. %. U-bearing minerals occur mainly as uranophane and b-uranophane (Fig. 16) in the oxidized horizons as idiomorphic crystals filling voids and as coatings on the crack surfaces of the albitized and alkali-feldspar granites.

**Table 9.** Selected microprobe analyses of PGE-bearing phases (Wt. %) in the southern central and Eastern Desert chromitites of Egypt (data from [47]).

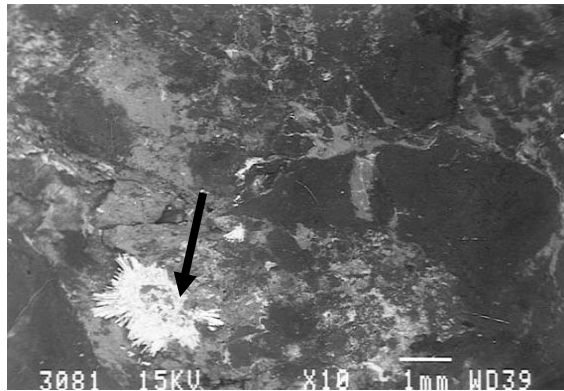
PG E	Sulfides	Os-Ir alloy	Ru-Os-Ir alloy	Sulfarsenides	Arsenides
Os	27.9	70.8	17.4	0.1	nd
Ir	5.6	21.9	14.1	53.6	nd
Ru	29.9	4.8	62.6	3.1	nd
Rh	0.7	0.2	3.6	3.1	1.9
Pt	nd	nd	nd	0.6	47.4
Pd	0.26	0.3	nd	nd	11.5



**Fig. 15** Geological map of the basement complex in Egypt showing the locations of potential occurrences of fissionable elements (modified from [20]).

According to Dawood et al. [49], trachyte from El Atshan area has higher U contents (67-1280 ppm) as a

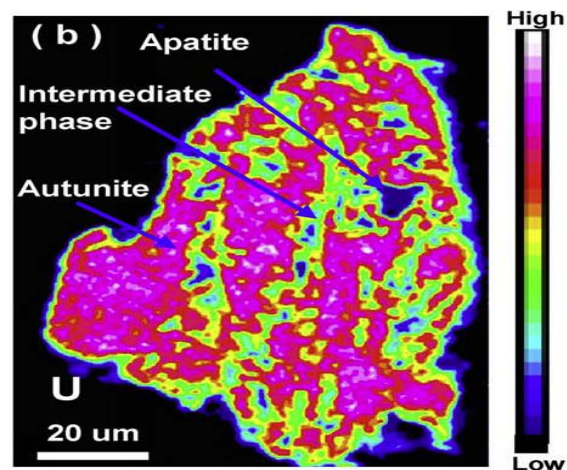
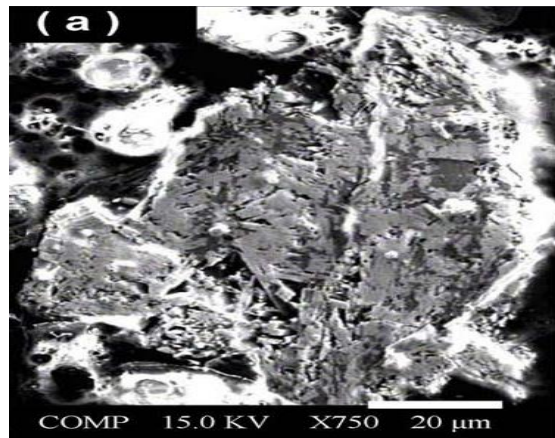
result of supergene enrichments of U due to the weathering of trachyte in this area. Therefore, U in this area occurs as secondary U-bearing minerals. Chemical analysis of the secondary uranium deposit from El Atshan region revealed approximately 7.7 wt. % of U.



**Fig. 16** SEM of cluster of needle-shaped uranophane crystals (arrow) filling a voids in the host granites [48].

Abd El-Naby and Dawood [50] examined the natural decrease of U during low temperature alteration of the Sela granite, south Eastern Desert. They pointed out that a pre-existing hydroxyapatite was altered to autunite by an unidentified intermediate mineral phase (Fig. 17).  $\text{UO}_3$  contents in the hydroxyapatite vary from 5.6 to 9.5 wt. % and in the intermediate phase from 23.4 to 40 wt. %, while in the autunite range between 57.6 and 67.6 wt. %. Ibrahim et al. [51] reported three types of secondary uranium minerals in the two mica granite of Gabal Ribdab region, South Eastern Desert, namely uranophane, becquerelite and zippeite (Fig. 18). Zippeite [ $2\text{UO}_3 \cdot \text{SO}_3 \cdot n\text{H}_2\text{O}$ ] is an orange mineral and formed as stains on mafic minerals and iron oxides. Becquerelite ( $2\text{UO}_3 \cdot 3\text{H}_2\text{O}$ ) is yellow in color and coexists with uranophane.

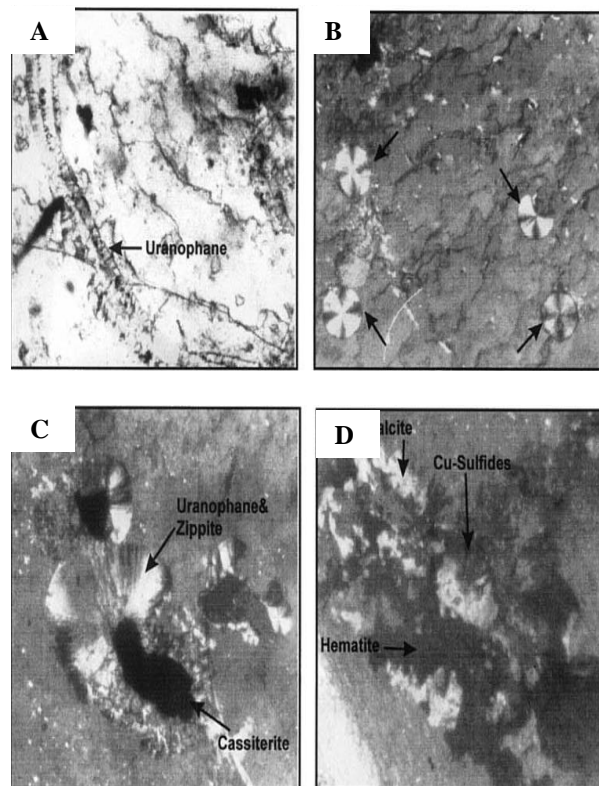
Uranophane [ $\text{Ca}(\text{UO}_2)_2(\text{SiO}_3)_2(\text{OH})2.5\text{H}_2\text{O}$ ] is also yellow in color and presents as soft aggregates on muscovite and quartz. The three minerals are considered as the alteration product of primary U-bearing minerals and associated with carbonatization and hematitization processes. The average of U content in the two-mica leucogranite is 20 ppm (range: 4-140 ppm), that in muscovite flakes is 11 ppm (range: 1-30 ppm) and that in the muscovite pegmatitic granite is 13 ppm (range: 2-40).



**Fig. 17** A) BSE image illustrates subparallel tabular crystals of autunite hosting hydroxyapatite laths. B) ray maps of U [50].

Meta-autunite, boltwoodite, uranophane and soddyite occur as yellow crusts and acicular crystals (Fig. 19) in the fractures, voids and shear zones in the psammitic gneisses of the Abu Rusheid area, Eastern Desert [48].  $\text{UO}_2$  contents at the meta-autunite vary between 68.5 and 76.3 wt. %, in the uranophane range between 64.2 and 67.3 wt. %, in the boltwoodite range between 58.3 and 63 wt. %, and in the soddyite range between 54.3 and 71.4 wt. %. At the Kab Amiri area, Central Eastern Desert, El-Hussaini et al. [15] reported high concentrations of U in the monzogranite (Table 10).

Feldspathized nepheline syenites in the inner parts of El Naga, Nigrub, El Fogani, and Abu Khrug areas, Eastern Desert are associated with relatively high concentrations of U (130-520 ppm) [28].

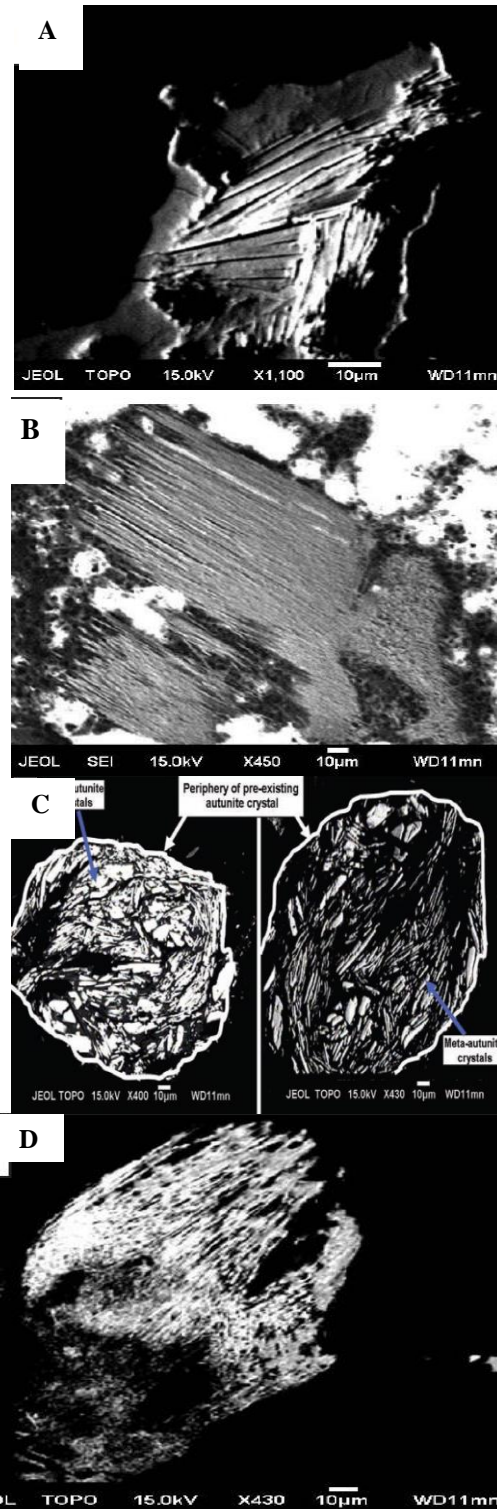


**Fig. 18** A) Veinlet of uranophane mineral filling fractures in muscovite. B) Open filling uranophane in muscovite. C) Secondary U-bearing minerals associate with cassiterite. D) Hematite, Cu-sulfides and calcite coexist with the uranium minerals [51].

**Table 10.**  $U_2O_8$  at the Kab Amiri area in different grain sizes (data from [15]).

Grain Size ( $\mu\text{m}$ )	Weight (%)	$U_2O_8$ (%)
-500	8.2	17.5
-420	6.6	12.5
-297	6.1	9.0
-250	10.6	13.3
-125	17.2	17.5
-74	51.3	30.1

Uranium in the Abu Tartur phosphorites ranges from 15 to 34 ppm (average 22 ppm) [12], which is lower than that in the Nile Valley (46-114) [53] and Red Sea phosphorites (35-143 ppm) [52]. Uranium probably cannot be considered as a possible byproduct as a result of its low concentrations (13-65 ppm) [53].



**Fig. 19** A) BSE image illustrates fan-shaped uranophane crystals, B) bendable and thin meta-autunite crystals, C) fibrous crystal clusters of soddyite, D) boltwoodite crystals [48].

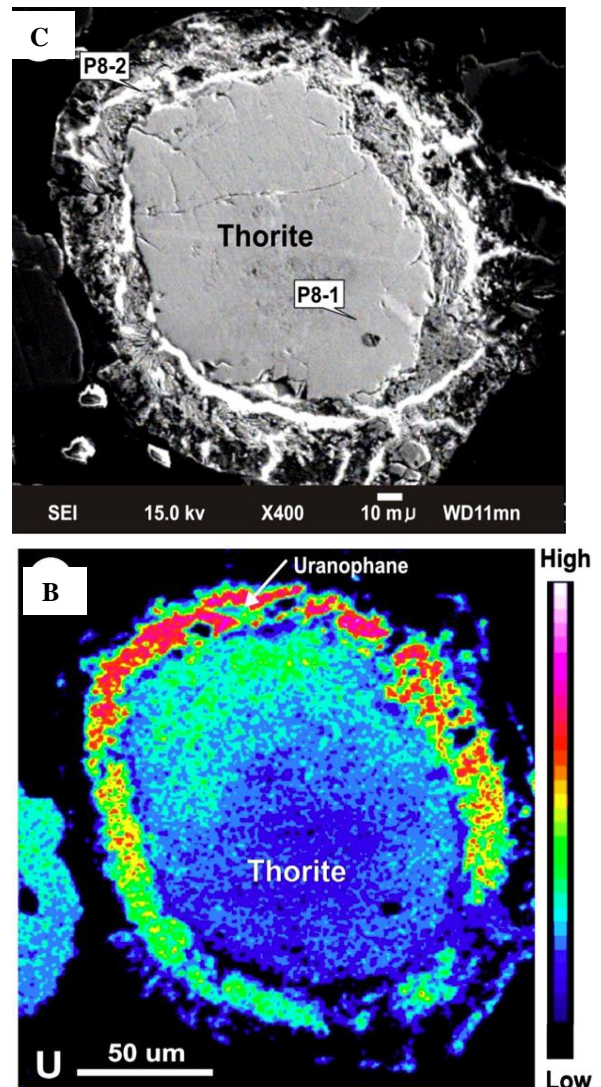
### 2.4.2. Thorium (Th)

Monazite that is composed of REE and Th phosphate ((Ce,La,Nd,Th)PO<sub>4</sub>) in the black sands along the Mediterranean Sea Coast can be considered as one of the potential sources of Th in Egypt (see REE part). Abd El-Naby [54] identified a number of thorium existences in granitic rocks at the Um Ara area, south Eastern Desert. Thorite, U-rich thorite and zircon are the major primary U- and Th-bearing minerals in the mineralized horizons of the Um Ara alkali-feldspar granites, while uranophane is the most abundant secondary U-bearing mineral. U-rich thorite comprises galena, rims of uranophane and inclusions of Zr-rich thorite (Fig. 20). ThO<sub>2</sub> contents in the thorite grains range from 68.4 to 72.1 wt. %, while UO<sub>2</sub> contents range between 5.9 and 7 wt. %.

At the Kab Amiri area, Central Eastern Desert, El-Hussaini [15] reported high concentrations of Th in the monzogranite in addition to the U (Table 11). Feldspathized nepheline syenites in the inner parts of El Naga, Nigrub, El Fogani, and Abu Khrug areas, Eastern Desert are associated with anomalous concentrations of Th (1420-8400 ppm) [28].

### 2.5. Processing and extraction of rare metals in Egypt

Although rare metals are quite common in Egypt and some of these metals occur in association as the abovementioned review shows, processing and extraction attempts of these metals are very limited compared with the potential occurrences of these metals. As for beneficiations of the rare metals in Egypt, few published attempts have been found during this review. Abd El-Rahman et al. [55] studied the recovery of fine cassiterite from Iгла placer deposits using falcon gravity separator and high intensity wet magnetic separation. Falcon separation concentrate containing 24.1% SnO<sub>2</sub> and recovery of 88.7 % by weight SnO<sub>2</sub> was obtained from a feed containing about 0.1 % SnO<sub>2</sub> that were cleaned by wet high intensity magnetic separation to 87 % SnO<sub>2</sub> and recovery of 95 % SnO<sub>2</sub>. Although there are many attempts to upgrade the phosphorites in Egypt for the manufacturing of fertilizers and production of phosphoric acid [56,57,58], the processing of REE were not considered in these attempts.



**Fig. 20** A) Secondary electron image of thorite with uranophane rims. B) X-ray map of (A) for uranium, indicating zoning in the thorite [54].

**Table 11.** Distributions of ThO<sub>2</sub> at the Kab Amiri area in different grain sizes (data from [15]).

Grain Size (µm)	Weight (%)	ThO <sub>2</sub> (%)
-500	8.2	10.0
-420	6.6	7.8
-297	6.1	6.9
-250	10.6	10.6
-125	17.2	17.2
-74	51.3	47.5

Moustafa and Abdelfattah [59] designed a flow sheet to concentrate monazite from Egyptian beach sands comprising around 30 wt. % valued heavy minerals. In this flow sheet, low specific gravity gangue is removed by wet gravity concentration, then low intensity magnetic separation is applied to remove any ferromagnetic minerals without eliminating paramagnetic monazite. Rutile is removed as it reports to the conductor fraction after electrostatic separation (zircon and monazite are non-conductive) and then diamagnetic zircon is removed from the paramagnetic monazite using additional magnetic separation.

An attempt to extract rare metals from the Egyptian ores was conducted by El-Hussaini et al. [15]. In this study, the Kab Amiri Nb- and Ta-bearing granites were subjected to direct agitation leaching by sulfuric acid. When finely ground ore (-74  $\mu\text{m}$ ) was reacted upon for 2 h with a combination of sulfuric acid (10.8 M) and nitric acid (5.3 M) in the ore to acid weight ratio of 1:3 at 200 °C, almost comprehensive recovery of both Nb and Ta was reached while the leaching degrees of Th and total REEs were 86 % and 70 %, respectively. Alternatively, the recovery of both U and Ti did not more than 60 % as a result of their occurrence in the refractory mineral davidite. Nb and Ta have been separated from the leach liquor using the tertiary amine, Alamine 336, by kerosene and xylene as diluents and n-decanol as a modifier [60].

As to the commercial scale of rare metals extraction, the only successful attempts to extract rare metals in Egypt are limited to the exploration and extraction of gold from a number of mines in the Sukkary (Centamine Limited) and Hamash (Hamash Co.) areas, Eastern Desert. In both areas, commercial production has just started using surface, open pit-open cast mining techniques [14,61].

### 3. Discussion

The rare metals were classified into four classes based on their chemical properties including rare earth, trace, noble, and fissionable elements in order to discuss their occurrences, industrial uses, and market. However, the critical review of the rare metals in Egypt suggested another classification in Egypt based on their host rocks to maximize the possible industrial utilization of the rare metals as well as their host rocks and minerals. The classification include three associations: 1) rare metals hosted by granites, 2) rare

metals associate the mafic rocks and ophiolites, and 3) rare metals occur in the sedimentary rocks.

Granites are extensively distributed in the Eastern Desert and Sinai as part of the Precambrian basement complex of Egypt [20] including the albite-granites. According to the abovementioned review, these granites include numerous numbers of rare metals such as REE in the Kab Amiri area, gold and silver in more than 95 localities mainly in the granites, niobium and tantalum in the granites at the Jabal Gattar and albite-granites at the Abu Dabbab, Nuweibi, Um Naggat, Abu Rashid, and Kab Amiri areas, uranium at the granites of the Um Ara, El Atshan, Gabal Ribdab, Abu Rusheid, El Naga, Nigrub, El Fogani, and Abu Khrug areas, Tin-Tungsten-Molybdenum association at the granites of the Igla, Abu Marwa, Gattar, Abu Harba, Um Disi and Homer Akarm, Abu Dabbab, Abu Hammad, and Um Bisilla, Muelha, Fatira, Abu Kharif, and Nuweibi areas, and thorium at the granites of the Um Ara an, Kab Amiri area. In addition to the rare metals contents of these granites, these granites are composed of feldspars especially albite in the albite-granites, quartz and mica (muscovite and biotite). Therefore, the utilizations of these granites for possible extraction of these metals can also include the extraction of these minerals that have many industrial applications such as abrasive, crucibles, computers, mobile phones, wristwatches, clocks, radios, navigational instruments, and television receivers for quartz and glass and ceramics industries for the feldspars, and paint, drywall compound, electronics, plastic, filler, and rubber for micas. Although the literatures showed that Kap Amiri granites have high concentrations of REE, NB, Ta, U, and Th, which makes these granites as potential source of these metals, the reserves, mineralogy, and mode of occurrence of these metals are not clear.

Mafic rocks and ophiolites represent a major portion of the Precambrian basement complex in Sinai and Eastern Desert [29,47]. Some important rare metals occur in these rocks such as cooper-nickel-cobalt association at the gabbro of the Abu Swayel, El Geneina, and Gabbro Akarem areas as well as the platinum group metals (PGM). These rocks are composed of gabbros and sometimes associated with chromite, serpentine, magnesite, and talc. Therefore, the utilizations of these mafic rocks and ophiolites for possible extraction of the cooper-nickel-cobalt-PGE can also include the utilization of the associated minerals that have industrial applications such as refractory and stainless steel for chromite, plastic, paper making, paint

and coatings, rubber, electric cable, food, pharmaceuticals, cosmetics, and ceramics for talc, decorative stone and carving stone tools for serpentine, and slag former in steelmaking furnaces, and binder in flooring materials.

Sedimentary rocks-bearing rare metals in Egypt are mainly phosphorites, black sands, and black shales. Phosphorites are one of the major deposits in Egypt (~ 3 billion tons' reserves) (Notholt, 1985; 9] are exploited for domestic industries and export as raw materials from different areas via several companies such as Red Sea Phosphorite Co. (Red Sea phosphorites), Abu Zabaal Phosphate Co. (Nile Valley phosphorites), and Phosphate Misr Co. (currently at Abu Tartur area). However, the attempts to extract REE from these phosphorites are almost absent to the best knowledge of the author. The extraction of REE from the phosphorites requires detail investigations on the behaviors of these elements during the different treatments and steps of utilizations. For example, during the chemical treatments of the phosphorites to produce phosphoric acid, it is important to follow the fractionations and forms of REE in the ore itself, in the phosphoric acid, and/or in the phosphogypsum cake. According to Habashi [62], when the phosphorite rock is treated with  $H_2SO_4$ , the lanthanides are mostly (~ 70 %) missed in the gypsum filtrate. When the phosphorite is treated with  $HNO_3$  or  $HCl$ , more than 80 % can be recovered without interference with fertilizer production. The extraction of REE from the phosphorites can be part of integrated industrial plant that can produce fertilizers, phosphoric acid, gypsum, and REE. In the Red Sea area, these phosphorites are associated with black shales beds with relatively high organic matter. This organic matter is rich in vanadium [37] that can add another economic value to the phosphorites and the associated black shales.

Large reserves of black sands occur along the Mediterranean Sea coast [13]. These black sands are composed of several minerals like ilmenite, magnetite, hematite, rutile, zircon, and monazite (REE- and Th-bearing mineral). Therefore, the utilizations of these black sands for possible extraction of the REE and Th can also include extraction of these minerals that are considered as potential sources of metals such as Ti from the rutile and ilmenite, Fe from the hematite and magnetite, and Zr from the zircon. These metals have numerous industrial applications such as steel and its alloys for Fe; manufacture of wide diversity of metal parts where very high strength and light weight are required like artificial joints for humans, aircraft parts

and sporting tools such as bicycle frames from Ti; and variety of high temperature applications for Zr. Thus, the integrated utilizations of these metals in addition to the rare metals can add significant values to the black sands deposits in Egypt. Although these black sands occur in relatively large reserves and can be exploited easily, only few published attempts have been found during this review on processing of these sands to extract valuable metals and elements [59] and almost nothing was found about the distribution of REE and Th in these black sands. The presence of some radioactive elements (Th and probably U) that needs special laboratory precautions to deal with these deposits could be the reasons behind the lacking of publications on these black sands in the international level like many other mineral deposits in Egypt.

It is well known that the geology of Sinai Peninsula is very similar to that in the Eastern Desert especially for the Precambrian basement complex [20,63]. Therefore, potential occurrences of rare metals are expected in Sinai especially those hosted by the granites such as REE, Au, Nb, Ta, Sn, and W. The current work noticed lacking of published data on the occurrences of rare metals in Sinai.

#### 4. Conclusions

The critical review of rare metals in Egypt revealed the following conclusive remarks.

- 1- Rare metals are quite common in Egypt including rare earth, trace, noble, and fissionable elements.
- 2- Some of these metals occur in association in the same rock and ore such as REE-Th, Nb-Ta, Cu-Ni-Co, Au-Ag, and U-Th.
- 3- One rock can host variety of rare metals such as granites that are widely spread in the Eastern Desert and Sinai, hosts Au, Ag, REE, U, Nb, Ta, Th, Sn, W, and Mo.
- 4- These metals associate with other minerals of industrial applications like REE in the phosphorites and Nb and Ta with quartz, feldspars, and mica.
- 5- Processing and extraction attempts of these metals in Egypt are very few compared with the potential occurrences of these metals.
- 6- Phosphorites deposits, as a major potential resource of REE in Egypt, occur in large reserves (~ 3 billion tons) and are exploited from many localities. However, no attempts have been found to extract the REE from these phosphorites.
- 7- Although black sands are considered as one of the major natural resources of rare metals such as REE,



Th, and Zr, no published data were found about the rare metals contents or economic feasibility of these black sands and their rare metals contents.

- 8- The literatures showed that Kap Amiri granites have high concentrations of REE, Nb, Ta, U, and Th, which makes these granites as potential source of these metals. However, the reserves, mineralogy, and mode of occurrence of these metals are not clear.
- 9- No publications about occurrences of rare metals in Sinai Peninsula although it is expected to have potential occurrences of these metals since its geology is very alike to that of the Eastern Desert.
- 10- The commercial scale of rare metals utilization is limited to the exploration and extraction of gold from a number of mines in the Eastern Desert.

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