

# Rare Earths in Egypt: Occurrence, Characterization and Physical Separation, A Review

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## Abstract

Rare Earth Elements (REEs) consist of the fifteen lanthanide elements plus scandium and yttrium, and can be found in more than 250 minerals. They exist in reasonable abundance in the Earth's crust, but mining sites contain too small REEs concentration to be valuable for separation. Cerium, yttrium, lanthanum, and neodymium are the most abundant REEs in the crust with similar abundances to commonly mined nickel and zinc metals. However, their extraction is almost impossible as they are found in deposits with very low concentrations. These elements are applied in various modern applications, including high-tension magnets, additives for metal and glass, petroleum refining catalysts, and phosphors used in electronic displays. REEs never existed as pure metals, while they are found in many minerals, including carbonates, halides, oxides, phosphates and silicates. Bastnäsite, monazite, and xenotime, as REE-bearing minerals, could be mined economically. They could be recovered using gravity, magnetic, electrostatic, and flotation techniques. This review examines the mineralogy, characterization and physical separation techniques currently used for the beneficiation of Egyptian rare earth minerals and spots localities that require further research.

**Keywords:** Rare earth elements, Monazite, Bastnäsite, Occurrence, Physical separation.

## 1. Introduction

Rare earth elements (REEs) include the fifteen Lanthanide elements along with Yttrium and Scandium as chemically similar elements [1-6]. Approximately 250 minerals contain rare earth oxides (REO) which could be categorized according to their REE composition into two principal categories; Cerium group (enriched with light rare earths) [LREE] and yttrium group (enriched with heavy rare earths) [HREE]. Bastnasite and monazite represent cerium group while xenotime, fergusonite, and samarskite represent Yttrium group [7-10].

As a result of their distinctive electrical, optical and magnetic characteristics, REEs are very common and applied in various fields of life. Although they are used in producing glass, lighting, and catalysts, they are also applied in developing markets such as alloys of batteries and permanent magnets, Fig. 1 and Table 1.

The continuously increasing demand for REE necessitates finding new methods of recovery [11-15].

REEs have significant occurrence in the earth's crust when compared with other common elements such as Pt, Ag, Au and Hg [16]. REEs never exist in pure form, but they are usually associated with silicates, oxides, carbonates, phosphates, and halides [17, 18].

REEs are considered as strategic metals and their estimated production in 2020 exceeded 200 kilo tons, Fig 2 [19, 20]. REEs production increased from 100,00 tons in 2011 to 200,000 tons in 2019 According to the data of the US Geological Survey reported in 2020 [19]. Up to 63% of REEs are produced in China with 33% of total REE reserves. Nevertheless, Egypt is not included in the survey as there are no estimated reserves or mine production of rare earths. Based on REEs production data, the top six rare-earth-producing countries include: China, USA, Burma, Australia, India and Russia [19].

The recovery investigation of REE from their bearing minerals is vital in order to overcome the lack of data related to their separation. Actually, the literature presents detailed studies on the occurrence of REE worldwide and their applications including REE mineralogy as well as their hydrometallurgical processing [1-8]. However, there is a lack of knowledge concerning their physical separation [1]. Given the increasing demand for these elements as well as the deposits' nature, the current knowledge of REE recovery should be developed [3]. This review displays the previous work published on the occurrence, characterization, and physical separation of Egyptian REEs.

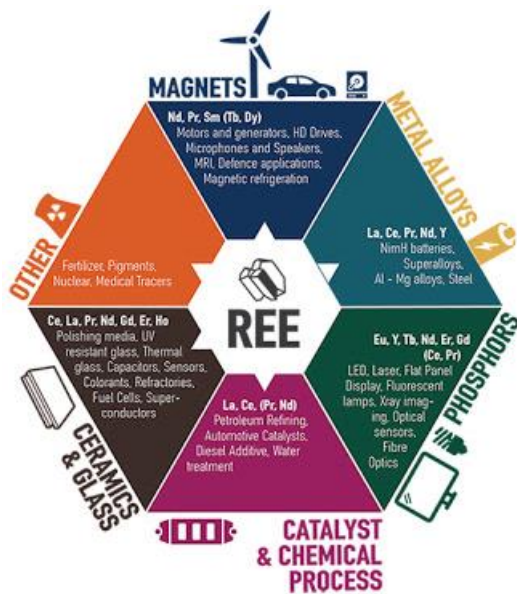


Fig.1 Rare earth elements applications [1, 5].

Table1. Percentage of rare earth elements applications [1, 5].

REE Applications	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Others
	(%)										
Magnets			23.4	69.4			2.0	0.2	0.2	5.0	
Battery Alloys	50.0	33.4	3.3	10.0	3.3						
Metal Alloys	26.0	52.0	5.5	16.5							
Auto Catalysts	5.0	90.0	2.0	3.0							
Petroleum Refining	90.0	10.0									
Polishing Compounds	31.5	65.0	3.5								
Glass Additives	24.0	66.0	1.0	3.0						2.0	4.0
Phosphors	8.5	11.0				4.9	1.8	4.6		69.2	
Ceramics	17.0	12.0	6.0	12.0							53.0
Others	19.0	39.0	4.0	15.0	2.0		1.0				19.0

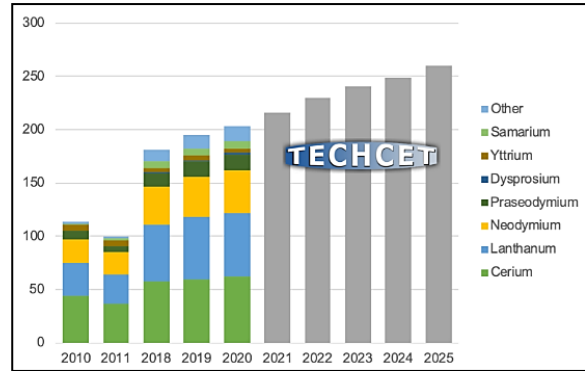


Fig. 2 Global REO production in kilo tons 2010-2025 [20].

## 2. Common Exploited REE Minerals

Among 250 identified REE-bearing minerals, the commonly exploited REE minerals are:

**2.1. Bastnäsite** [(Ce, La, Y) CO<sub>3</sub>F], a fluorocarbonate mineral, contains up to 75 wt. % REO. It is the most abundant LREE mineral. It is found in vein deposits and pegmatites [8]. It is paramagnetic with a density range 4.9-5.2. Bastnasite is located in Egypt in peralkaline granites in the Southwestern Desert [21-23].

**2.2. Monazite** [(Ce, La, Nd, Th) PO<sub>4</sub>], a phosphate mineral, contains up to 70% REO and is a primary source of LREE [8]. Monazite is rich in radioactive as it includes up to 12 wt.% thorium and as high as 14 wt.% uranium. Monazite is found throughout Egypt in placer deposits and beach sand [24].

**2.3. Xenotime** [YPO<sub>4</sub>], a yttrium phosphate mineral, contains up to 65% REO. It has thorium and uranium content. The mineral is tetragonal, with a hardness of 4-5 and a density of 4.4-5.1. It is separated as a by-product with monazite and zircon. In Egypt, xenotime is found in granite pegmatites in the Eastern desert [13, 24].

**2.4. Fergusonite** [YNbO<sub>4</sub>], yttrium niobate, is composed mainly of yttrium and niobium with tetragonal symmetry [25].

**2.5. Samarskite** [YFe<sup>3+</sup>Fe<sup>2+</sup>U,Th,Ca)<sub>2</sub>(Nb,Ta)<sub>2</sub>O<sub>8</sub>] is a radioactive REE mineral that contains up to 35% REO. It exists in granite pegmatite sand associated with monazite, zircon, columbite, albite and biotite [26].

**2.6. Allanite** [(Ce,Ca,Y)<sub>2</sub>(Al,Fe<sup>3+</sup>)<sub>3</sub>(SiO<sub>4</sub>)<sub>3</sub>(OH)] is a sorosilicate mineral that contains 20% REO. It is mainly used in dating geological processes due to its efficiency in the storage and mobility of REEs and Th [1].

### 3. REEs in Egypt: Occurrence and Characteristics

REEs never discovered in pure form, but they exist as silicates, oxides, carbonates, phosphates, and halides minerals [4].

#### 3.1. The granitic pegmatites

The Egyptian granites are a primary source of industrial minerals (feldspars, quartz), high-tech mineral stocks (Li, Cs, Nb, Ta, Sn, and REEs) and radioactive (Th and U)[27]. Many Egyptian granitic pegmatite areas were reported such as G. Ras Baroud, G. Abu Dob, Ras Mohamed, Gabal El Fereyid, Abu Rusheid and Abu Dabbab [28, 29].

##### 3.1.1. Wadi Al-Baroud

Wadi Al-Baroud area exist at latitude range: 26° 43' 21" and 26° 48' 50" N and a longitude range: 33° 32' 50" and 33° 40' 08" E near the Northern-Central Eastern Desert, Fig. 3. The rocks include feldspar and quartz with recorded radioactivity [30]. The heavy mineral content includes 0.74 wt.% REE, zircon, Nb-Ta oxides, and Th minerals. Monazite, xenotime, and allanite are the main REE-bearing minerals.

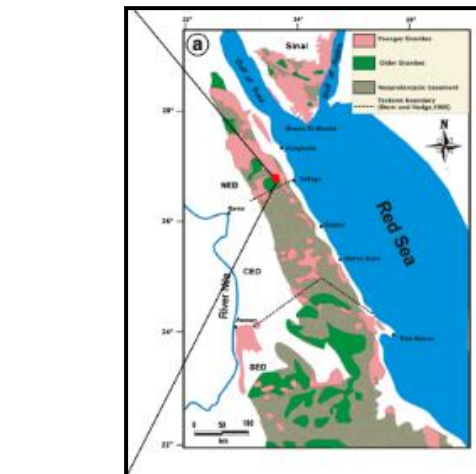
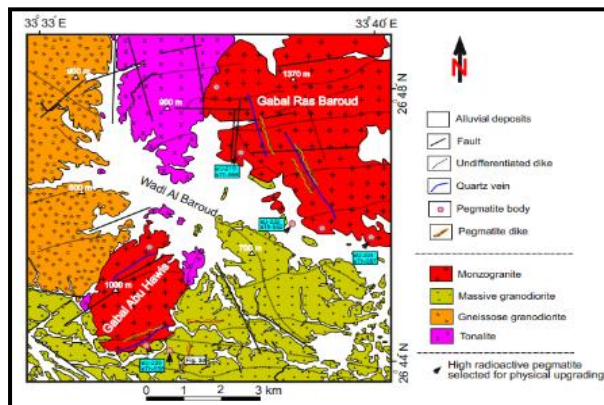


Fig. 3 Geological map of Wadi Al-Baroud area [30].

#### - Characteristics of Wadi Al-Baroud REEs:

**Monazite-(Ce)** occurs in all size fractions, Fig. 4a, b. analyses revealed that it is enriched in Ce<sub>2</sub>O<sub>5</sub> (27.4 wt.%), La<sub>2</sub>O<sub>3</sub> (12.5 wt.%), and Nd<sub>2</sub>O<sub>3</sub> (12.36 wt.%).

**Xenotime-(Y)** is massive, translucent, and hard with granular form with thorite inclusions, Fig. 4c-f.

**Allanite** exists as black transparent crystals, Fig. 4g.

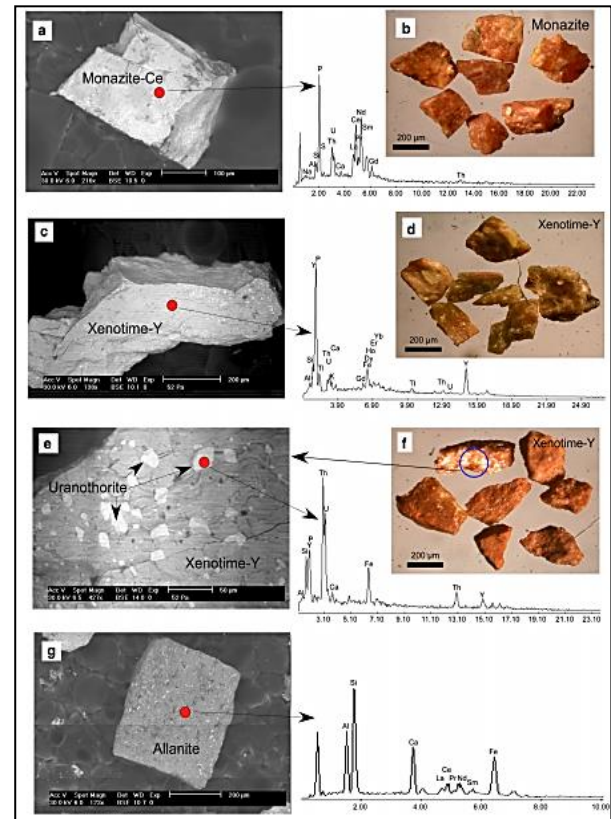


Fig. 4. BSE and EDX of a, b) monazite-Ce, c, d) xenotime-Y, e, f) uranothorite in xenotime and g) allanite [30].

##### 3.1.2. Wadi Abu Dob

Gabal Abu Dob exists in the Central Eastern Desert of Egypt. It is located at latitude 26° 40' N and longitude 33° 20' E, Fig. 5. It is existed as anhedral cluster. This area was reported by Many authors such as Ibrahim et al. [31], Ibrahim [32], Attawiya et al. [33], and Ammar [34].

#### - Characteristics of Wadi Abu Dob REEs

**Fergusonite-Y**: [(Y, REE)Ca, U, Th] (Nb, Ta)O<sub>4</sub> has massive grains with granular form and is Nb-rich, Fig. 6. This structure was confirmed using XRD, Fig. 7.

**Titanite - Allanite-Ce** [(Ca, REE, Th)<sub>2</sub> (Fe<sup>2+</sup>, Al)<sub>3</sub> Si<sub>3</sub>O<sub>12</sub> (OH)] exists in a large transparent crystal, Fig.6.

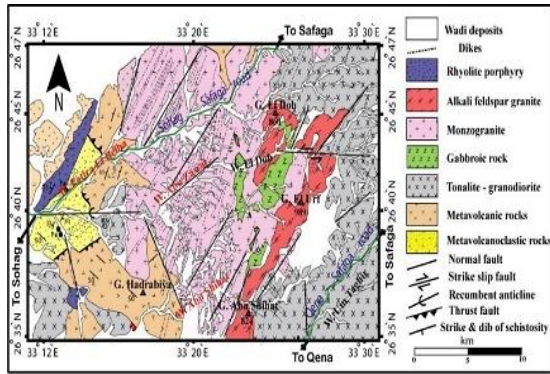


Fig. 5. Geological map of Wadi Abu-Dob area [25]

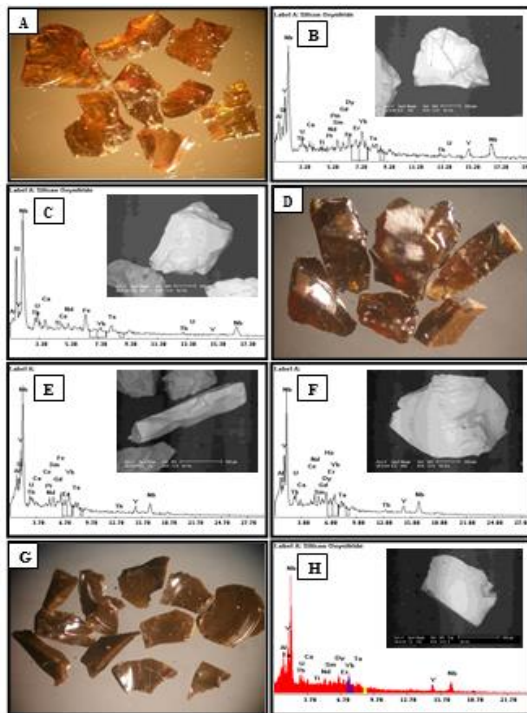


Fig. 6. Fergusonite with A) yellowish brown color, D) velvet-yellow brown color, and G) deep brown color. EDX and BSE of B, C) yellowish brown fergusonite, E, F) velvet-yellow brown fergusonite, and H) deep brown fergusonite [25].

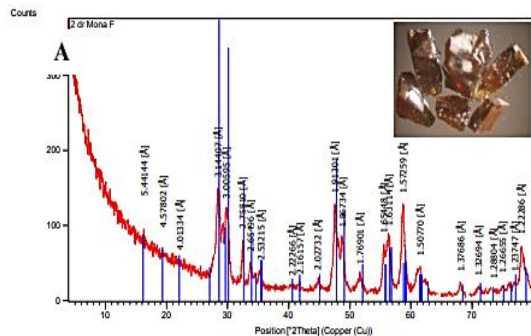


Fig. 7 X-ray diffraction of fergusonite [25].

### 3.1.3. Gabal El Fereyid

It is located at latitude 23° 15' - 23° 19' N and longitude 35° 22' - 35° 22' E in south Eastern Desert, Fig. 8. [35].

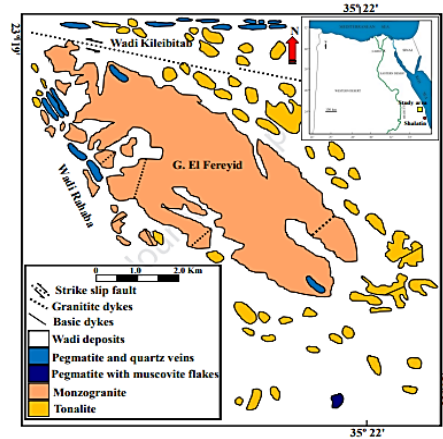


Fig. 8 A geologic map of G. El Fereyid area, South Eastern Desert, Egypt [28].

#### - Characteristics of Gabal El Fereyid REEs

These pegmatites contained thorite ( $\text{ThSiO}_4$ ), uranothorite ( $(\text{Th}, \text{U})\text{SiO}_4$ ), monazite, zircon, fergusonite, samarskite with traces of titanite and allanite minerals, Fig. 9. The total content of REEs is up to 250 ppm [28]. When compared with Abu Rusheid area [36], they show lower contents, Table 2.

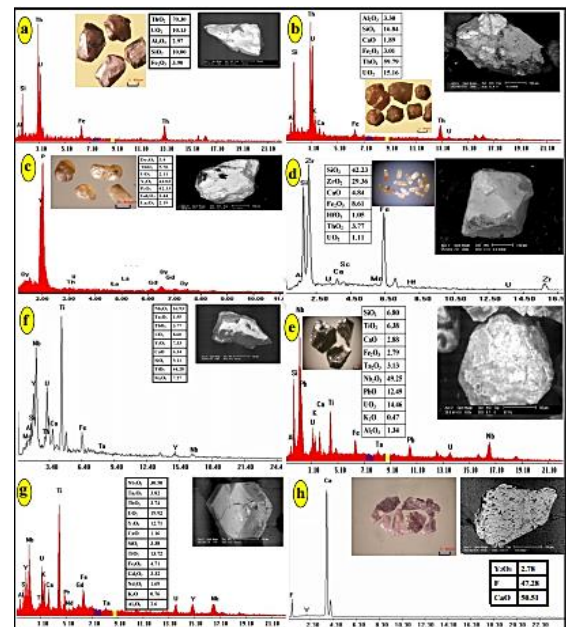


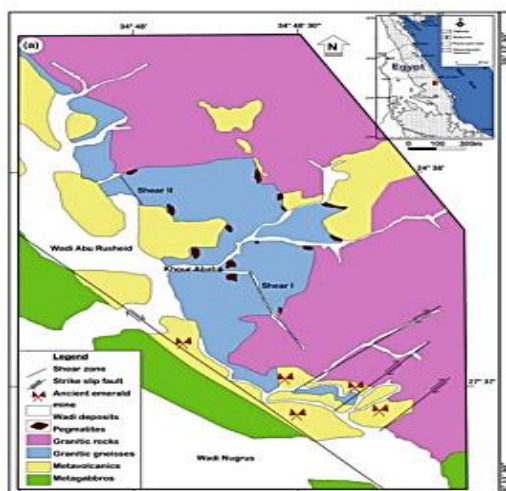
Fig. 9 SEM and EDX of a) Thorite, b) Uranothorite, c) Monazite, d) Zircon, e) Fergusonite, f) Samarskite, g) Ishikawaite and h) fluorite of G. El Fereyid [28].

**Table 2.** REEs content in Abu Rusheid area compared to Gabal El Fereyid [36].

REE	Abu Rusheid area	Gabal El Fereyid
	REEs in ppm	
La	26.70	1.10
Ce	113.32	4.93
Pr	3.50	0.60
Nd	8.80	1.80
Sm	9.30	0.80
Eu	0.80	0.10
Gd	12.10	0.80
Tb	4.90	0.40
Dy	53.10	4.40
Ho	5.70	1.20
Er	23.90	5.20
Tm	12.40	1.10
Yb	111.10	9.70
Lu	16.50	1.40

### 3.1.4 Abu Rusheid

Abu Rusheid area is located at the southeastern desert, 90 km at the south of Marsa Alam, Fig. 10. Abu Rusheid granite include quartz, K feldspar, oligoclase and biotite with amounts of Nb, Ta, Sn and Zr [37].



**Fig. 10** Abu Rusheid locality, Egypt [36].

#### - Characteristics of Abu Rusheid REEs

**Samarskite**, with the empirical formula  $(Y, Fe^{2+}, U, REE)(Nb, Ta)O_4$ , is found with columbite and monazite [36].

**Allanite** exists in pegmatites as an irregular crystal in feldspar combined with zircon.

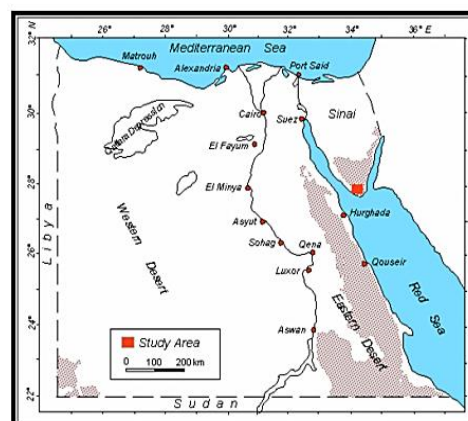
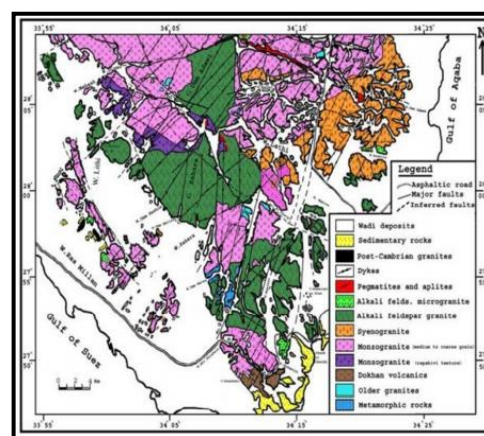
**Monazite** primarily existed in Abu Rusheid pegmatites in combination with xenotime, columbite, and zircon.

**Xenotime** is uriferous and associated with fluorite and hematite.

The total REE amount in pegmatite ranges from 30 to 450 ppm with a 0.1 LREE/HREE ratio. The pegmatites of Abu Rusheid displayed a higher amount of REE than that of Gabal El Fereyid, Table 2 [36].

### 3.1.5. Ras Mohamed

Ras Mohamed is in the Southern part of Sinai at latitude  $27^{\circ} 47' - 28^{\circ} 9' N$  and longitude  $33^{\circ} 55' - 34^{\circ} 24' E$ , Fig. 11. The area is intersected by the provincial road between El-Tour and Sharm El-Sheikh Cities



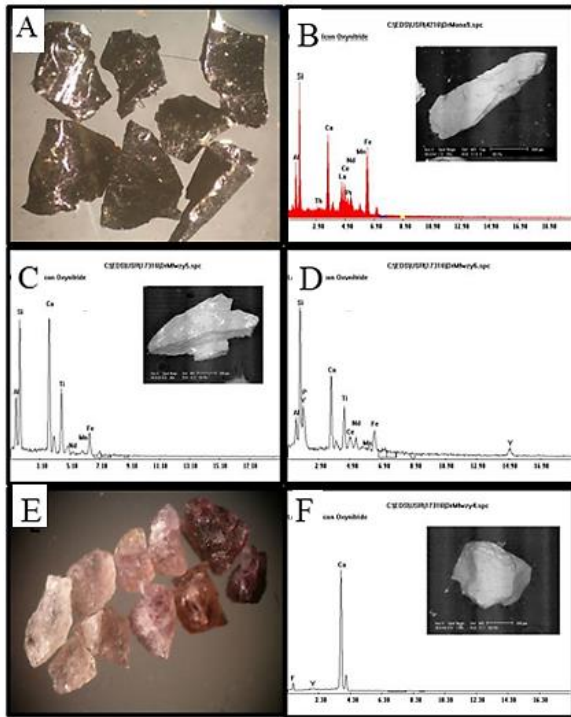
**Fig. 11** Geological map of Ras Mohamed locality [38].

#### - Characteristics of Ras Mohamed REEs

**Allanite**:  $[(Ca, REE, Th)_2 (Fe^{2+}, Al)_3 Si_3O_{12} (OH)]$  exists as black large transparent crystals (Fig. 12A, B).

**Titanite**:  $[CaTiSiO_5]$  exists as large transparent crystals of anhedral to subhedral shape and is enriched in  $Y_2O_3$  due to xenotime substitution (Fig. 12C, D).

**Fluorite**:  $[CaF_2]$  exists as transparent crystals having multi colours (Fig. 12E, F). El-Kammar et al., (1997) displayed that the colour variation is due to the Y content and is referred to radioactivity effect [39].



**Fig. 12** A) allanite; EDX and BSE of B) allanite; C) titanite; D) EDX of bright inclusions in titanite; E) colourless, rose and pink fluorite crystals; F) BSE and EDX of fluorite [38].

### 3.1.6. Nusab El Balgum

Nusab El Balgum is a peralkaline volcanic rock that exists in the Southwestern Desert at longitude 29°18' and latitude 23°17', Fig. 13. This locality is rich in REEs as well as Nb, Th, and U. [22].

#### - Characteristics of Nusab El Balgum REEs

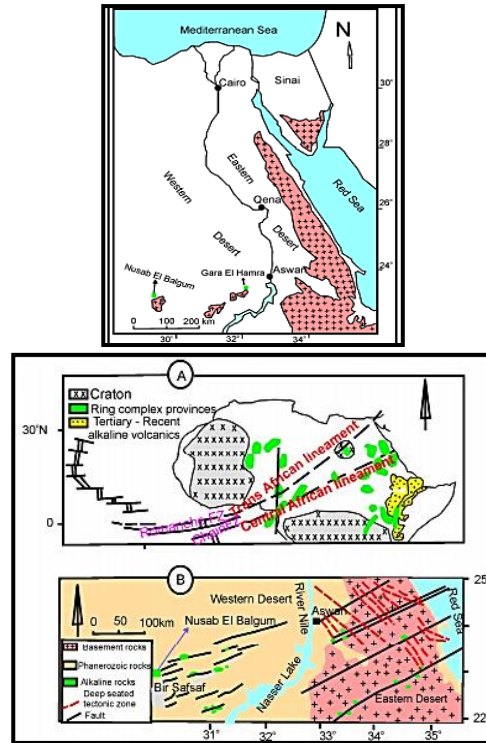
**Bastnaesite:** [(CeCO<sub>3</sub>) (OH, F)] is Cerium fluorocarbonate with transparent luster. It is identified by XRD, Fig 14.

**Monazite** is a monoclinic form that is stable at wide range of temperatures and pressures [22].

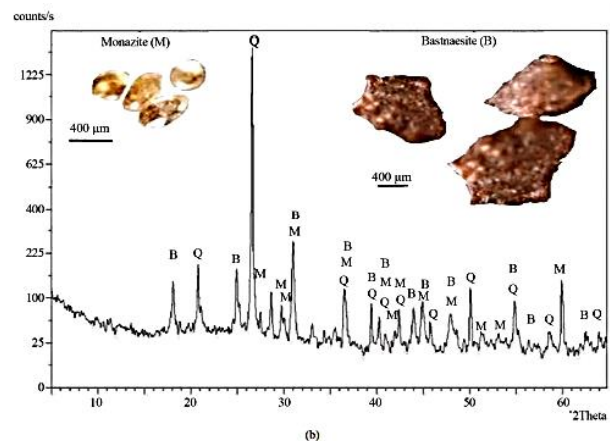
### 3.1.7. El Seboah Area

El-Seboah acidic peralkaline mass is located in the Southwestern Desert at Longitude 31°53' 56" E and Latitude 22°45' 48" N, Fig. 15. El-Seboah granites occur as a small stock intruded into Nubia sandstones from the most northwest part.

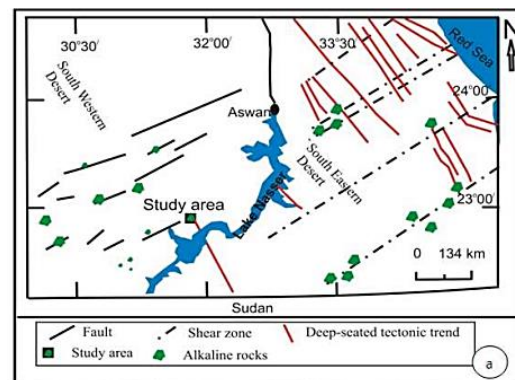
Extreme enrichments in rare metals characterize these rocks such as: Zr (1 wt.%), Nb (0.1 wt.%) and total REEs (0.5 wt.%), with some radioactives (U 54 ppm and Th 685 ppm). The rare metals bearing minerals are bastnaesite, thorite, uranothorite and zircon.



**Fig. 13** Geological map of Nusab El Balgum [22].



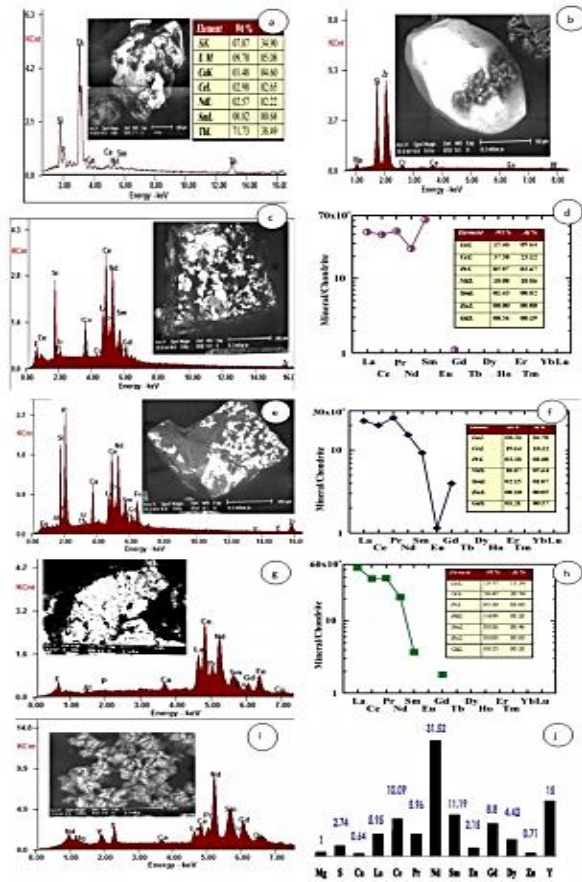
**Fig. 14** XRD and photomicrographs for monazite (M) and bastnaesite (B) [22].



**Fig. 15** Geological map of El-Seboah locality [23].

**Characteristics of El Seboah REEs**

**Bastnaesite:** [(CeCO<sub>3</sub>) (OH, F)] exists in carbonate and alkaline igneous rocks, Fig. 16.



**Fig. 16** ESEM/ EDX of a) uranothorite, b) zircon, c, d) percentage of REES for zircon and flourapatite, e, f) LREE percentages for composite grain (zircon and monazite), g, h) LREE percentages for bastnaesite mineral and I, j) percentages of REO [23].

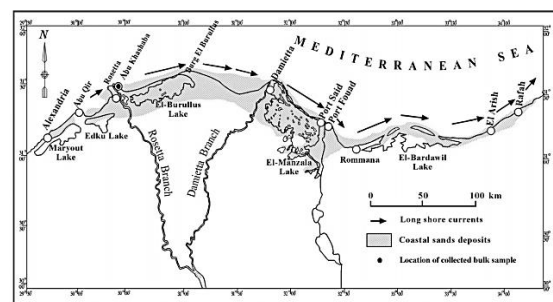
**3.2. Black Sand**

The Egyptian black sand, along the Mediterranean coast, represents great reserves of many economic minerals such as ilmenite, magnetite, garnet, zircon, rutile, and monazite with low concentrations of cassiterite and gold. The overall estimated reserves of these minerals are about 31000 metric kilotons at the first meter and 616000 metric kilotons at the first twenty meters from the top, Fig. 17 [40, 41]. These sand deposits exist as beach sediments as well as coastal sand dunes. The most suitable deposit localities are as follows: Rosetta, El Burullus-Baltim, Damietta, and north Sinai, Fig. 18. Monazite content is usually below 0.01 wt.%. Butit may reach up to 0.6 wt.% in some

areas. Monazite is a primary source of REEs with some radio actives thorium and uranium) [42].

The estimated reserves of the black sand, Monazite, Zircon and Rutile as well as Radioactives and REEs are shown in Table 3 [43].

Dawood and Abdel-Naby (2007) reported the black sand monazite from Sinai as a primary source of REE, Fig. 19 [44]. The essential minerals in black sand deposits are iron–titanium oxides (magnetite, hematite, ilmenite and rutile). They contain zircon, monazite. Garnet (Pyr<sub>49</sub>Alm<sub>42</sub>Gros<sub>5</sub>Sp<sub>2</sub>And<sub>1</sub>) is recorded in the Egyptian black sand with content up to 1.83 wt.%. Investigations of Egyptian black sand showed an Y and high REEs content [41-44].



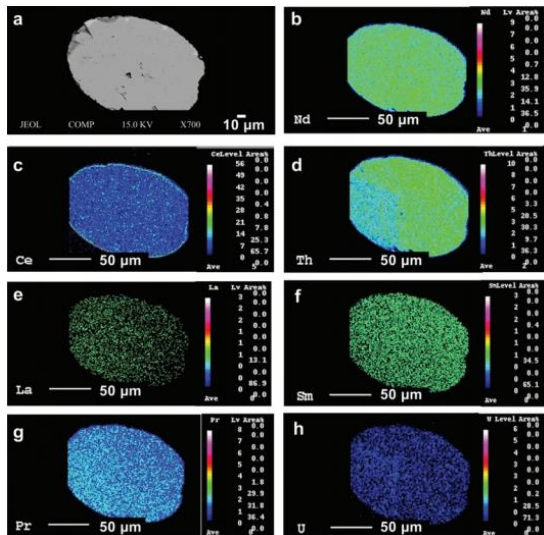
**Fig. 17** Geological map of Egyptian black sand along the Mediterranean coast [41]



**Fig. 18** Field photo from the Egyptian black sand .company, National Service Projects Organization (NSPO) [42].

**Table 3** Estimated reserves of Egyptian black sand: Monazite, Zircon and Rutile as well as Radioactives and REEs at Rosetta, Baltim, Damietta and Sinai [43].

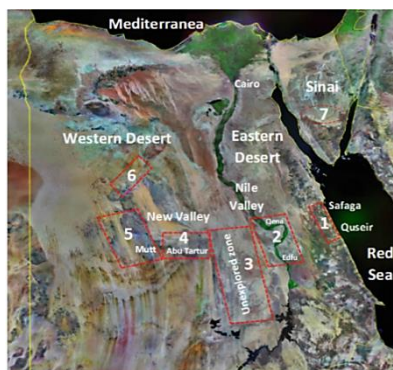
	Unit	Rosetta	Baltim	Damietta	Sinai	Total
Length	(m)	70,000	15,000	30,000	20,000	135,000
Width	(m)	800	800	1,000	500	----
Depth	(m)	9	15	10	10	----
Volume	(m <sup>3</sup> )	494 x 10 <sup>6</sup>	180 x 10 <sup>6</sup>	300 x 10 <sup>6</sup>	100 x 10 <sup>6</sup>	1074 x 10 <sup>6</sup>
Weight	(t)	839 x 10 <sup>6</sup>	306 x 10 <sup>6</sup>	510 x 10 <sup>6</sup>	170 x 10 <sup>6</sup>	1825 x 10 <sup>6</sup>
Monazite	(t)	167,960	61,200	102,000	34,000	356,160
Zircon	(t)	1,847,560	673,200	1,122,000	374,000	4,016,760
Rutile	(t)	1,007,760	367,200	612,000	204,000	2,190,960
U <sub>2</sub> O <sub>7</sub>	(t)	1,915	698	1,163	388	4,164
ThO <sub>2</sub>	(t)	10,884	3,966	6,610	2,203	23,663
(Zr +Hf) <sub>2</sub>	(t)	1,238,974	451,448	752,413	20,804	2,693,639
TiO <sub>2</sub>	(t)	995,272	362,647	604,411	201,470	2,163,800
RE <sub>2</sub> O <sub>3</sub>	(t)	103,531	37,724	62,873	20,958	225,086



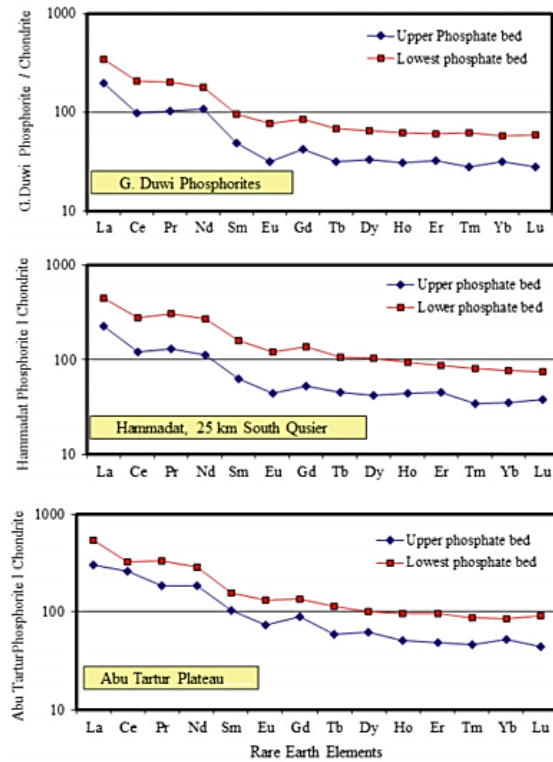
**Fig. 19** (a) EMP-BSE image of monazite from Northern Sinai beach. (b-h) Monazite mapping (b) Nd; (c) Ce; (d) Th; (e) La; (f) Sm; (g) Pr; and (h) U [44].

### 3.3. Phosphate Ores

Phosphate deposits are laminated superficial marine sedimentary rocks usually accompanied by black shale, limestone, and glauconite, Fig. 20 [45]. The REE in phosphorites could be used as a by-product of the phosphoric acid industry and is also vital in assessing a good understanding of the depositional environments [6]. Although phosphorites were discovered more than 100 years ago in Egypt, the geochemistry and economic significance of REE were reported for the first time by El-Kammar in 1974, then many researchers studied REE in phosphorites [45-49]. The classification of REE in Egyptian phosphates is heterogeneous. LREE (La, Ce, Pr, Nd, Sm, and Eu) present more than 80% of total REE content. REEs content of phosphates is correlated with Sc and Th. Various phosphate localities are rich in REE (+1000 ppm), Fig. 21. The upper layers of phosphate include less than half REE of the lowest layers [49].



**Fig. 20** Occurrence of phosphate rocks in Egypt [45].

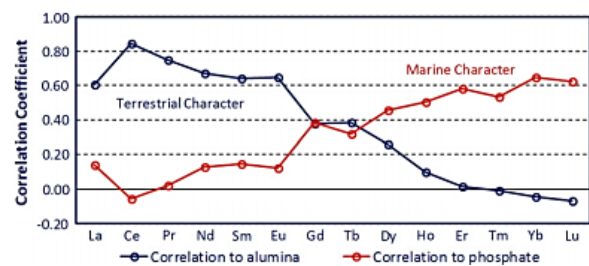


**Fig. 21** REEs of upper and lower phosphate layers of some localities in Egypt [45].

### 3.4. Oil Shale

The companies of phosphate production are located in Quseir – Safaga at Red Sea and waste great amount of oil shale. This oil shale covers the extracted phosphates, causing collapses and self-ignition for miners. The oil shale could deteriorate when exposed to atmospheric conditions so that it is not sampled [50].

The REE dispersion in oil shale displays both marine and terrestrial contribution to the depositional basin. The results present the terrestrial affect by the LREE and the marine by HREE. LREE contribution supports an obvious monazite form while HREE presents a xenotime form. In all cases, the LREE contribution to the total REE content is much higher than the HREE, Fig 22.



**Fig. 22** REE for terrestrial and marine indicators [50].



#### 4. REEs in Egypt: Physical Separation

The recovery of REE minerals primarily uses the differences in density, magnetic and electrical characteristics, and surface chemistry of REE minerals and accompanied gangue minerals. Hence, they could be recovered via physical separation techniques (gravity, magnetic, electrostatic, and flotation methods) [1, 13, 51]. A primary ore concentration using physical methods would minimize the consumed acids during the leaching of REE low-content ores. It could also be useful in disposing of tailings safely. Most of REE minerals are recovered via the association of many physical methods [24].

Actually, there is a lack in the research and development of Egyptian rare earth mineral beneficiation. This section reviews the published work on the physical separation techniques employed in the separation of Egyptian REE minerals.

##### 4.1. Gravity Separation

REE are good nominees for gravity separation due to their high densities (4-7) and their accompanied gangue minerals, which have lower densities [13].

Wilfley shaking table is the most widely used, as a wet gravity separator, to upgrade Egyptian rare earth-bearing minerals [25, 26, 30, 37, 41]. REE particles are arranged with the highly dense particles on the table bottom. As a consequence of decreasing riffles taper, the upper surface of the rearranged material is acting via water crosscurrents as well as the inclination angle moving downhill [52, 53].

Monazite is usually recovered with gravity methods. Moustafa and Abdelfattah, 2010, studied the upgrading of monazite from Egyptian beach sand, and a concentrate comprising up to 30 wt.% of valuable heavy minerals was achieved [41]. They employed a Wilfley shaking table to discard the light gangue from valuable heavy minerals including monazite. Subsequently, low-intensity magnetic separators were applied to separate ferromagnetics without removal of paramagnetic monazite. The remained fraction contains the valuable minerals (monazite, zircon, and rutile) [41].

Raslan and Fawzy 2018, studied the physical separation of fergusonite from Wadi Abu Dob locality [25]. They applied Wilfley shaking table on different size fractions in order to have a pre-concentrate, Table 4. The table optimum parameters were: feed rate (5 kg/hr), water flow rate (4 L/min), stroke length (1.0 cm) and an inclination angle of 8° degree. The produced concentrate contained fergusonite and zircon. The final

concentrate had heavy minerals of 72.56% with a 79.58% recovery [25]. Therefore, a combination of gravity, magnetic, and electrostatic separation methods should be applied [1, 13].

**Table 4** Chemical analysis of shaking table products of Wadi Abu Dob ore [25].

Size fractions (mm)	Shaking table Products	Wt. (%) Overall	Assay % H.M.	Distribution (%)
-1.00 + 0.700	Conc.	9.3	95.9	25.34
	Tail	16.8	11.9	5.68
	Feed	26.09	35.2	31
-0.700 + 0.500	Conc.	8	69.7	17.4
	Tail	8.5	2.0	0.53
	Feed	16.48	32	17.8
-0.500 + 0.250	Conc.	9.2	61.2	20.40
	Tail	13.87	2.2	1.10
	Feed	23.07	27.6	21.5
-0.250 + 0.125	Conc.	3.2	86.2	10.97
	Tail	10.27	1.6	0.65
	Feed	13.47	25.2	11.5
-0.125 + 0.063	Conc.	2.9	49.8	5.47
	Tail	6.02	10.7	2.44
	Feed	8.92	26.4	7.9

##### 4.2. Magnetic Separation

Magnetic separation employs the distinctions in magnetic susceptibility behavior of REE minerals and the gangue minerals when exposed to magnetic fields of different intensities. The minerals are categorized into three different classifications according to their magnetic field behavior: ferromagnetics, paramagnetics and diamagnetics.

REEs generally have electrons with magnetic moments that occupy the 4f sub-shell, leading to REEs magnetism. REEs are highly paramagnetic excluding La, Sc, Lu and Y. Therefore, they hold diverse magnetic characteristics based on the abundance of paramagnetic or diamagnetic elements accessible in the mineral. At low temperatures, paramagnetic REEs suppose ferromagnetic nature when exposed to a magnetic field [13, 51].

HREE has higher paramagnetic values than LREE. Xenotime has more HREE content than monazite, this may illustrate its higher magnetic susceptibility than monazite [1].

In REEs separation, a magnetic technique is applied to separate ferromagnetic Fe-bearing minerals, as a primary step to upgrade the existing REEs. Moustafa M. I. (2007), displayed that magnetic separation has been very instrumental in the beneficiation of Egyptian monazite from beach sand as well as magnetite separation before separating monazite from non-magnetic minerals [54]. He classified the Egyptian black sand heavy minerals according to their magnetic

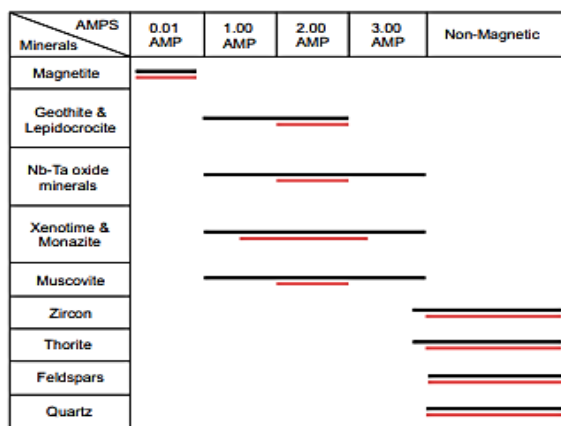
susceptibility, Table 5. Leucoxene is not a mineral; it is an alteration product of ilmenite.

**Table 5** The magnetic classification of the Egyptian black sand heavy mineral varieties [54].

Ferromagnetic Minerals	Paramagnetic Minerals		Non-Magnetic Minerals
	Strongly-Moderately	Weakly	
Magnetite	Ilmenite	Monazite	Gold
Feri-Ilmenite	Garnet	Xenotime	Cassiterite
Magnetic Zircon	Mag. Zircon	Uranothorite	Zircon Rutile
	Ferriferous Rutile	Zircon	Kyranite
	Mag. Leucoxene*	Leucoxene	Sillimanite
	Pyroxenes	Hematite	Apatite
	Amphiboles	Hemo-Ilmenite	Sphene
	Epidote	Chromite	Saturiolite
		Cassiterite	Other trace minerals

Usually, magnetic separation is applied for two reasons: namely the low-intensity magnetic separation to separate ferromagnetic Fe minerals and the high-intensity magnetic separation to recover monazite and xenotime from zircon as illustrated by Fawzy et al., 2020, Fig. 23 [30]. Raslan and Fawzy 2018, subjected the tabling concentrate of Wadi Abu Dob ore to the Carpc high-intensity magnetic separator to obtain pure concentrates of each fergusonite and zircon [25]. Where the magnetic materials are raised up counter gravity compared to other separators.

The Separation of fergusonite was achieved as a magnetic fraction at optimum Carpc parameters: magnetic field (1-1.5 amp.), roll speed (50 rpm), and feed rate (150 g/min). The final magnetic fergusonite concentrate was assayed 98% while the non-magnetic zircon concentrates were assayed 96% [25].



**Fig. 23** The optimum field intensity for separating various minerals from Wadi Al-Baroud locality using Carpc high-intensity magnetic separator [30].

### 4.3. Electrostatic Separation

Various minerals display different conductive features when subjected to an electric field.

Electrostatic separation uses the electric field forces to make similar attraction and repulsion between mineral particles in order to separate them [55]. Separation is based on the capability of a mineral to gain and reserve electric charge when applying high voltage.

The factors controlling the separation are: the magnitude and polarity of charge, the distance between the charged regions, and the particle's di-electric constant [24]. Mineral particles could be charged with conductive induction, ion bombardment or tribo-electrification. This technique was applied in upgrading xenotime and monazite from gangue minerals with similar densities and magnetic features [1, 13, 51].

Moustafa M. I. (2007) utilized the electrostatic separation in the beneficiation of Egyptian black sand [54]. He had classified the Egyptian black sand heavy minerals according to their conductivity, Table 6.

**Table 6.** The classification of the Egyptian beach heavy minerals during the high-tension electrostatic separation [54].

Conductors		Non-Conductors
Good	Poor	
Gold	Magnetic Zircon	Monazite
Cassiterite	Garnet	Zircon
Magnetite	Non-magnetic Leucoxene*	Green Silicates
Ilmenite		Apatite
Hematite		Kyanite
Chromite		Picotite
Rutile		Xenotime
Magnetic Leucoxene*		Uranothorite
Other trace minerals		Sillimanite

Moustafa and Abdelfattah (2010), studied the behaviour of monazite from Egyptian black sand with the electrostatic separation [41]. The studied variables are, high voltage (KV), radial distance (d, mm), angular position ( $S^\circ$ ), electrode diameter (m), feeding rate (g/min). Monazite particles had reversible negative charge and were attracted towards the positively charged static electrode. When monazite is accompanied with magnetic zircon, it acts as reversible positive while zircon acts as reversible negative [41].

### 4.4. Multi-Stage Separation of Egyptian REEs

Due to the low grade of Egyptian REE-bearing minerals, a multi-stage separation is recommended to achieve an efficient beneficiation process. Multi-stage separation involves applying gravity, magnetic, and electrostatic separations series.

#### 4.4.1. Separation of Monazite

Egyptian black sand contains various economic minerals. These deposits are presented as beach sand or

coastal sand dunes. Moustafa M.I., 2007, evaluated the sand dunes from El Burullus-Baltim locality [56]. The total estimated minerals content is 4.66% and divided as follows: ilmenite, 3.41%; magnetite, 0.27%; garnet, 0.52%; zircon, 0.31%; rutile, 0.14% and monazite, 0.01%.

Gravity, magnetic and electrostatic separation methods have been used to separate the valuable minerals from each other. The light silicate minerals were eliminated via Wilfley table, The primary concentrates were treated with low-intensity magnetic separator to eliminate magnetite as a ferromagnetic fraction, then ilmenite and garnet were collected as paramagnetic fraction while zircon, rutile, and monazite were collected as nonmagnetic fraction. Using two individual circuits of high-tension electrostatic separation, ilmenite is obtained as conductors in the deflected fractions and garnet as non-conductors in the adhered fractions in the first circuit.

In the other circuit, rutile is obtained as conductors in the deflected fractions while zircon and monazite are obtained as non-conductors in the adhered fractions.

Zircon was obtained as a nonmagnetic fraction when applying high-intensity magnetic separator while monazite was obtained as a magnetic fraction.

Pure magnetite, ilmenite, zircon and rutile were obtained in assays that reached up to 99.99% and recoveries of 95.3%, 75.5%, 77.8% and 77.3%, respectively [54].

Then, Moustafa and Abdelfattah 2010, suggested a flowsheet to recover monazite from Egyptian beach sand with 30 wt.% heavy minerals, Fig. 24[41].

In this flowsheet, light fraction is eliminated using shaking tables then low-intensity magnetic separators were conducted to separate magnetite. The non-magnetic stream contains monazite, zircon and rutile. A series of physical separations were applied to separate them. Rutile is separated as a conductor with electrostatic separation (monazite and zircon are nonconductors). Subsequently, the paramagnetic monazite was separated from the diamagnetic zircon using magnetic separation [41].

#### 4.4.2. Separation of Xenotime and Monazite

Fawzy et al., 2020 applied gravity and magnetic separation processes to upgrade Wadi Al-Baroud ore [30]. The sample had 0.03% REE. The upgrading of was achieved via Carpc magnetic separator to obtain a concentrate of paramagnetic fraction and another of diamagnetic fraction. Non-magnetic fraction was applied as a feed, for Wilfley gravity table to separate zircon. The optimized conditions were; inclination

angle (8 degrees), stroke length (1.0 cm), feed rate (5 kg/h) and water flow rate (4 L/min). The produced concentrates have mainly zircon with low thorite content.

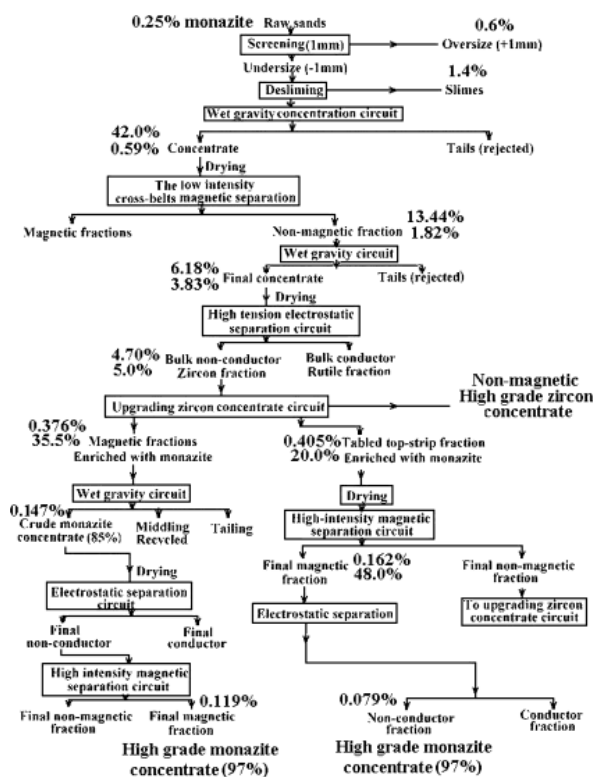


Fig. 24 The suggested flowsheet for separating Egyptian beach Monazite concentrate [41].

A final concentrate with 0.31% REE and recovery of 86.19% was obtained when applying the optimum conditions. Therefore, the final concentrate would be treated via hydrometallurgical processes to separate the valuable metal content [30].

#### 4.4.3. Separation of Samarskite-Y

An interesting study for separating samarskite-Y REE mineral from Ras Baroud area was achieved by Raslan M. F. 2009 [26]. In this study, a heavy mineral existence with a considerable samarskite (Y), 1.5 wt.%, was subjected to multi-stage separations. Raslan applied sieving, desliming, Wilfley gravity table and magnetic separator to have a samarskite (Y) concentrate as follows:

- A feed of Ras-Baroud area including samarskite-Y, columbite, zircon, magnetite, garnet, ilmenite, hematite and mica was prepared via desliming and sieving on 1 mm screen.
- Different sieved size fractions were separated via a Wilfley gravity table individually.

- Subsequently, the heavy fractions were exposed to low-intensity magnetic separator (LIMS) to separate magnetite and high high-intensity magnetic separator (HIMS) to obtain a non-magnetic concentrate of samarskite (Y) and zircon.

A final concentrate of 73.8 wt.% samarskite (Y) was obtained [26].

#### 4.4.4. Separation of Fergusonite-Y

Raslan and Fawzy, 2018, showed that Fergusonite-Y exists in Abu Dob locality at the Central Eastern Desert [25]. They suggested an intergrowth of minerals with Hf-Zircon. A multi-stage beneficiation process was applied via Wilfley gravity table and Carpc magnetic separators. A reasonable separation was achieved between fergusonite-Y and Hf-Zircon. Further treatments are required to obtain high fergusonite concentrate [25].

#### 4.5. Froth Flotation

Froth flotation is a flexible and adjustable method to separate minerals using their surface wettability variation. Flotation had high efficiency in beneficiating low-grade and complex ores [56].

Mineral particles may have an affinity for water and, hence, are wetted easily (hydrophilic) and others that repel water (hydrophobic). In a system of hydrophobic and hydrophilic particles mixture suspended in water, the hydrophobic particles are attached to the air bubbles floating to the surface, when air is presented [57, 58].

##### 4.5.1. Flotation of Fergusonite

The efficiency of the mixed anionic (sodium oleate)/nonionic (sorbitan monooleate) collectors for separating fergusonite from silicates has been tested during the flotation process. Fawzy, 2018, displayed that fergusonite recovery was increased using the mixed collector [59]. Flotation process was optimized and a good separation was reached at pH 5 with 1 Kg/Mg mixed collectors (1:1) in the presence of methyl isobutyl carbinol (MIBC) as a frother. Moreover, using sodium metasilicate, as a depressant, improved the flotation of fergusonite.

A cooperative interaction between the anionic and nonionic surfactants was distinguished during adsorption on fergusonite and separated it efficiently from silicates [59].

##### 4.5.2. Flotation of Xenotime

Fawzy et al., 2015, investigated the direct flotation of Xenotime-bearing ferruginous sandstone belonging

to Adediya formation of the lower carboniferous in Southwestern Sinai.

A direct froth flotation technique using a modified Hallimond tube and sodium oleate as a collector has been applied and the relevant factors were studied [60].

The maximum floatability of xenotime occurred at pH 7, grain size -0.05mm and  $10^{-5}$  M/L sodium oleate concentration. These conditions give 71.7 % xenotime recovery, assaying 83.6 %, but at the lowest weight recovery of about 20%.

The authors concluded that the anionic collector sodium oleate is chemisorbed onto the xenotime surface at the previous optimum conditions. This means that xenotime was increased in concentrate 3.6 times more than in feed.

It was supposed that primary separation using flotation could decrease the load on the hydrometallurgical extraction of xenotime [60, 61].

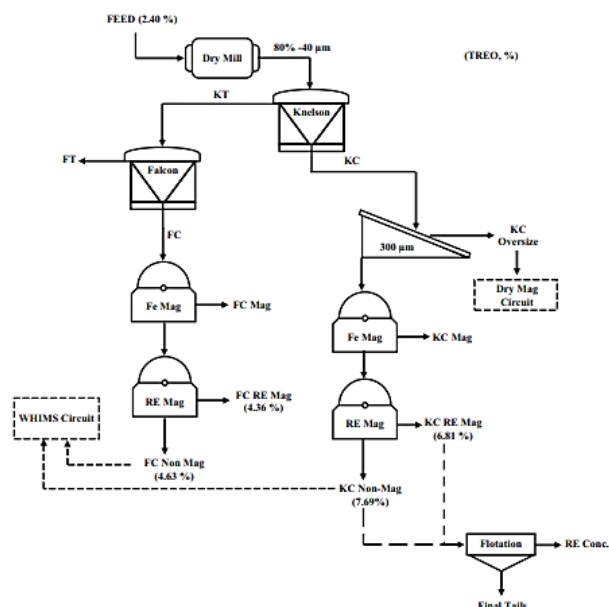
#### 5. Recommendations and Future Perspectives

Based on the findings in this research as well as the recent world trends, many perspectives and issues would be considered in future studies for the characterization and physical separation of Egyptian REE minerals.

The continuously increasing need for REEs necessitates looking for new investigations for their recovery. Although there is available data concerning the occurrence, mineralogy, and characterization of REE-bearing minerals in Egypt, there is a lack in the research and development of Egyptian RE mineral characterization and beneficiation as follows:

- Various phosphate localities including Hammadat south Quseir, south Edfu (e.g., in Fawaza and Silwa villages), and the lower bed of Abu Tartur plateau are remarkably rich in REE + Y (about 1000 ppm). However, there is no available data regarding their physical separation. All published work on Egyptian REE-bearing phosphate belongs to acid leaching and hydrometallurgical techniques [6, 62-64].
- Abu Rusheid locality is rich in REE-bearing minerals: however, the published work focused only on the physical separation of radioactive minerals [37, 65].
- Despite the importance of Bastnasite worldwide: There is a lack of data concerning the physical separation of this REE mineral in Egypt. The published work belongs to acid leaching and hydrometallurgical techniques [23].

- Essential information on the optimization of physical separation processes and complete characterization of produced products has not been detailed in the published research. This implies that a great deal of research is required to improve the separation of Egyptian REE minerals.
- In all published work, the Wilfley shaking table was applied as a gravity separation tool, but it could be interesting to apply centrifugal concentrators to upgrade Egyptian REE minerals. The processing of low-grade ores, which contain REE that are present in fine sizes, involves grinding to fine particle size to impart the liberation of valuable and gangue minerals. The shaking table is limited to ultrafine particles. Therefore, enhanced gravity separators, multi-gravity separators, Knelson, and Falcon concentrators are used for the recovery of ultrafine REE [51, 66]. Nechalacho deposit in Canada has 183.4 million tons of ore at a grade of 1.27% of total rare earth oxides. The beneficiation flowsheet includes gravity concentration and magnetic separation to enrich total REE values from 2.40 to 7.69%. A combination of Knelson and Falcon concentrators and magnetic separation has resulted in the enrichment of REE values to 7.69%, Fig. 25 [51, 67].



**Fig. 25** Nechalacho rare earth beneficiation flowsheet [51, 67].

- Only dry magnetic separators were used to upgrade Egyptian REE. However, wet high-intensity magnetic separators showed high efficiency in separating diamagnetic silicates from bastnaesite, allanite, and

ferugsonite [51]. Changsha Research Institute of Mining and Metallurgy suggested a flowsheet for beneficiating Bayan Obo rare earth mineral deposit, China. The recovery included various steps of magnetic and flotation separation. The achieved nonmagnetics were separated with tabling and flotation to obtain bastnaesite concentrates. The recovery process included comminution, LIMS/HIMS magnetic separators along with direct/reverse flotation [51, 68]. The HIMS non-magnetic fraction was treated with flotation using naphthyl hydroxamic acid as collector, J 10 as frother, and sodium silicate as a depressant for silicates. The pulp density was adjusted at a range of 35 - 45%. REO-rich concentrates were enriched up to 55% and 34% as flotation products, with an overall recovery of 72-75%. The REO-rich concentrates contained mainly bastnaesite and monazite, which were separated by floating bastnaesite using Phthalic/benzoic acids as collectors while depressing monazite using alum as a depressant [51, 68].

- Nowadays, phosphonium/ammonium ionic liquids are considered as promising collectors for the flotation of REE-bearing minerals [69]. The investigation of applying these ionic liquids in the beneficiation of monazite and bastnaesite has been explored. Ionic liquids displayed high efficiency in beneficiating REEs when compared to hydroxamic acid collectors. Both anionic and cationic parts of ionic liquid interact during REEs' flotation. This means that the adsorption of both cationic and anionic parts occurred completely [70, 71].

- Also, it should be taken into consideration that Phospho-gypsum and red mud are promising secondary sources of REE that would have much attention in order to achieve the growing requirements of REE.

The consequences of this research comprise new understanding regarding Egyptian REEs processing. Conclusions from this work may help REEs industry to enhance their beneficiation and cover part of REEs demand to enhance our technological level and modernity which is accompanied by producing new and multifunctional materials.

## 6. Concluding Remarks

REEs are very essential because of their industrial and high-tech applications. They are critical due to their limited consumable supply. Dysprosium, terbium, praseodymium, europium, and neodymium have high criticality levels in supply up to 2030. This is due to their fast-growing demand for producing permanent magnets, which are applied in hybrid electric vehicle

manufacturing and wind turbine generators for producing green energy.

As a result of their special electrical, optical, and magnetic features, rare earth elements are very popular and used in many different areas of life.

Various REE-bearing minerals are distributed in Egypt such as Monazite, Xenotime, Fergusonite, Samarskite and Allanite. However, Bastnasite is an abundant REE mineral, there is a lack of data concerning the physical separation of this mineral in Egypt.

Various phosphate localities such as Hammadat south Quseir, south Edfu, and Abu Tartur plateau are remarkably rich in REE + Y (~ 1000 ppm). Oil shale also has a significant content of REEs.

REE minerals beneficiation mainly exploits the differences in the specific gravity, magnetic, and electrical properties as well as surface chemistry of the REE minerals and the associated gangue minerals. Hence, they could be beneficiated using gravity, magnetic, electrostatic, and flotation separation techniques. Most RE mineral deposits are beneficiated through a combination of these unit operations.

Actually, there is a lack in the research and development of Egyptian REE beneficiation.

Due to the low grade of Egyptian REE-bearing minerals, a multi-stage separation is recommended to achieve an efficient beneficiation process. Multi-Stage separation involves the separation of minerals by applying a series of gravity, magnetic, and electrostatic separations on the ore containing REE bearing minerals in order to obtain high-grade concentrates. Flowsheets for Monazite, Xenotime, Samarskite-Y, and Fergusonite-Y from black sand and some granitic pegmatite areas were investigated.

Monazite from black sand deposits could be considered as the only valuable REE-bearing mineral that would be separated economically in Egypt.

Further research concerning the use of ionic liquids as promising collectors for the flotation of rare earth elements from their bearing minerals should be considered.

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