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ORIGINAL RESEARCH PAPER

Physical processing for polymetallic mineralization of Abu Rusheid mylonitic rocks, South Eastern Desert of Egypt

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ABSTRACT

In this study, the mineralogical content of Abu Rusheid mylonite sample was investigated and revealed that the sample is essentially composed of quartz and feldspar (72.14% mass), muscovite (16.6% mass), and contains heavy economic polymetallic minerals of about 2.65% by mass. By studying the differences in the physical properties of this mineral content, a proposed flow sheet was set up to explain the successive physical upgrading steps for concentrating and separating the valuable minerals content and getting rid of the associated gangue minerals. Industrial, economic and strategic polymetallic minerals were identified at Abu Rusheid mylonite sample, including cassiterite, titanite, brass, kasolite, monazite, and uranothorite. A group of sulfide minerals also existed as pyrite, arsenopyrite, galena, and molybdenite in addition to the presence of fluorite and iron oxides bearing rare earth elements (REEs) and base metals. Using dry high intensity magnetic separation followed by wet gravity separation and flotation, three concentrates were obtained; heavy paramagnetic concentrate (monazite, columbite, brass, and jarosite), heavy diamagnetic concentrate (zircon, kasolite, uranothorite, cassiterite, and sulphide minerals) and muscovite concentrate for industrial uses. Physical processing of Abu Rusheid mylonite sample was carried out to produce high grade mineral concentrate used as a raw material for chemical treatment to extract economic elements that necessary for several industries.

KEYWORDS

polymetallic minerals, gravity, magnetic, flotation, Abu Rusheid, Eastern Desert, Egypt

1. INTRODUCTION

The Arabian-Nubian Shield covers an area of about two million square kilometers on both sides of the Red Sea [1], and is determined by the limited exposure to the basement rocks beneath the extensive cover of undeformed Paleozoic strata in Sinai, Saudi Arabia, and Yemen. Precambrian basement in Egypt, Sudan, Ethiopia and parts of Uganda and Kenya and the northern coast of Somalia is described as Nubian Shield. The Egyptian Eastern Desert is divided into three main parts, the North, South, and Central Eastern Desert, based on characteristic changes in geological style [2]. Area of Abu Rusheid is located at the southern part of the Eastern Desert of Egypt and it is bounded by a major shear zone that known as Nugrus thrust fault [3] or the Nugrus strike-slip fault [4]. The shear zone separates high-temperature metamorphic rocks of the Hafafit complex in the SW from mainly low-grade ophiolitic and arc volcanic assemblages known as Ghadir group to the NE.

The granitic pluton of Abu Rusheid-Sikait was elongated in NW–SE (12 km in length) and thinning in NE–SW (3 km in width). The granitic pluton core was occupied by cataclastic rocks and is represented from the NW direction by porphyritic biotite granites followed by deformed biotite granites and two mica granites (abundant garnet and kyanite crystals), whereas the muscovite granites covered the SE part of the pluton [5]. The biotite granites can be classified into two phases; high deformed biotite and low deformed biotite granites.

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Most of economic polymetallic minerals are upgraded throughout a conjunction of different physical processing operations like gravity, magnetic and froth flotation. As a result of their relatively high specific gravities, gravity separation can be used to upgrade heavy minerals by rejection of low specific gravity associated gangue silicate minerals as quartz and feldspar. In the context of mineral physical beneficiation, magnetic separation techniques are common separation step that is used for two targets: elimination of ferromagnetic minerals as magnetite using low intensity magnetic separators, or upgrading the desired paramagnetic minerals (columbite, rutile, wolframite, monazite, xenotime, chromite, euxenite, fergusonite, and allanite) and separating them from the diamagnetic minerals using high intensity magnetic separators [6–14].

This study aims to characterize the mineralogical contents of Abu Rusheid mylonitic sample as well as investigate the most suitable physical beneficiation techniques for upgrading and producing high grade concentrate of industrial, economic, and strategic polymetallic minerals.

2. GEOLOGIC SETTING

Abu Rashid area is located in the southern part of the Eastern Desert of Egypt, about 95 km southwest of Marsa Alam City on the coast of the Red Sea (Fig. 1a). The studied area is covered by latitudes 24° 36′ 29″ to 24° 39′ 22″N and longitudes 34° 44′ 40″ to 34° 47′ 23″E (Fig. 1b). The Precambrian rocks are arranged chronologically from oldest to youngest as such (a) Ophiolitic metagabbros, (b) Ophiolitic mélange, (c) Cataclastic rocks, (d) Granitic rocks (e) Lamprophyre dykes, pegmatite and quartz veins [5, 15, 16]. The Precambrian rocks are subjected to polycyclic deformation events and are distinguished by regional WNW–ESE thrusting. The age of thrusting is between 682 Ma (the time of emplacement of the older granitites) and 565 to 600 Ma, the time of intrusion of the younger granites [2].

The layered ophiolitic metagabbros are thrusted over the ophiolitic mélange along WNW–ESE direction (Nugrus thrust fault) from south and southwest direction from low to high angles (30°). The ophiolitic mélange represent the hanging wall of the fault was thrusted over the cataclastic rocks. It comprises a metamorphosed sedimentary matrix (biotite-phlogopite schist, garnetiferous hornblende biotite schist, and garnetiferous staurolite schist) enclosing allochthons serpentinite, metagabbros and ortho-amphibolite fragments mounted in schists [15]. The cataclastic rocks of the area were represented by protomylonite, mylonite, ultramylonite, and silicified ultramylonite (quartzite) with gradational contacts. The color of the clastic rocks ranged from light gray to gray in color, fine to coarse-grained and

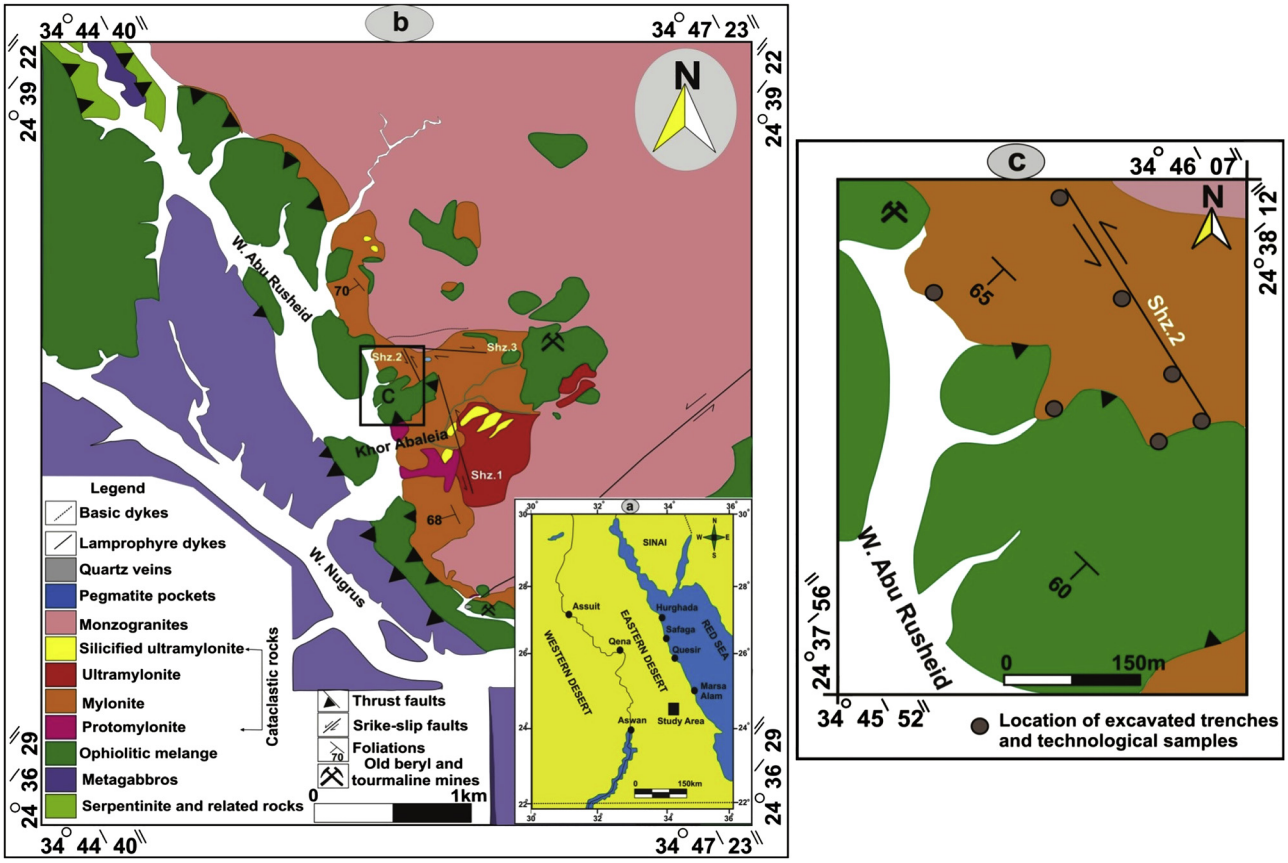

Fig. 1. (a) Abu Rusheid location map and (b) A simplified geological map of W. Abu Rusheid area (Ibrahim et al., 2004). (c) A simplified geological map of the investigated part of Abu Rashid area, reformed after (Ibrahim et al., 2004), symbols as in Fig. 1b

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exhibit layering between protomylonite and mylonite and It features enclaves. The enclaves mainly composed of mineralized black micas, irregular in shape (oval, elongated, semi-rounded) with variable dimension (10–30 cm). The cataclastic rocks contain blocks of mafic-ultramafic rocks and bands of tremolite-actinolite. They are highly sheared, banded (N–S) and cut by three shear zones. The first two shear zones strike NNW–SSE and differ in thickness from 0.5 to 1 m and have about 1,000 m in length. The third shear zone strikes ENE–WSW and varies in thickness from 0.5 to 1 m and 500 m in length. The shear zones were extruded by lamprophyre dykes with vertical dip. The latter are good trap for uranium, rare earth elements, copper, zinc, silver, lead and yttrium [17]. The cataclastics exhibit alteration, including albitization, silicification, kaolinitization, chloritization, fluoritization, and hematitization [18–20]. Abu Rusheid pegmatite presents in two forms; segregations and dykes which intruded into the cataclastic rocks of the area. The pegmatite veins have NNW–SSE trend with dip range from 10 to 30° toward WSW direction parallel to banding of the cataclastic country rocks. Abu Rusheid zoned pegmatite veins characterized by barren core and mineralized wall zone enriched by zirconium, niobium, yttrium, zinc, lead, and uranium [21].

The area of the second shear zone (Fig. 1c) and its contacts with the ophiolitic mélange are very promising for poly-metallic mineralization. The functions of these shear zones perform the entrapment and localization of uranium in the fractures that act as dam or stand in the way of propagating uranium bearing solutions. These stand that damming solutions that cause through channel change the direction of solutions and deflect them toward the SW in NNW–SSE or SE in ENE–SWS direction. This leads to the uprising of the solutions to somewhat higher level along these faults and shear joints and in these parts the solutions find it easy way to propagate and entrap through the adjacent subhorizontal and subvertical joints that cause the formation contouring shape lenses within and near shear zone. The ophiolitic melange rocks occur in southeast, north and northwest of the mylonite rocks of Abu Rusheid as capped rocks. These capped rocks play a very important role in the deposition of uranium under it for these reasons; 1 – The porosity of these rocks is very low, so that the solutions loaded by uranium cannot penetrate through it and 2 – The solutions which loaded by U and HFS elements contain F as indicate by field and mineralogical studies when attached and mixed mélange rocks will be deposited due to their change in pH and Eh as a result the change in composition. So, the cataclastic rocks of this area (mylonite) contain abundant crystals of uranophane, autunite, meta-autunite, kasolite, torbernite, columbite, zircon, xenotime, allanite, and monazite. Therefore, several trenches were excavated (Fig. 3) to appreciate the extension of this mineralization with depth. Occurrences of mineral diversity in the cataclastic rocks are essentially due to the mineralogical composition of the sedimentary protolithes and also due to the alteration effects and supergene processes. Several mineral varieties are inherited from the granitic rocks such as zircon and others are introduced to the rock by hydrothermal activity like fluorite, while other mineral variety has been formed by supergene enrichment as uranium minerals (Fig. 2a). Columbite–tantalite minerals are abundant in the form of fine grains that are dispersed either as a single crystal or as aggregates, which can be seen with the naked eye (Fig. 2b).

3. SAMPLING AND METHODOLOGY

Technological bulk sample from Abu Rusheid mineralized mylonitic rock weighting about 50 kg was used in this work. Initially, the technological sample was subjected to comminution processes (crushing and grinding) to diminish the

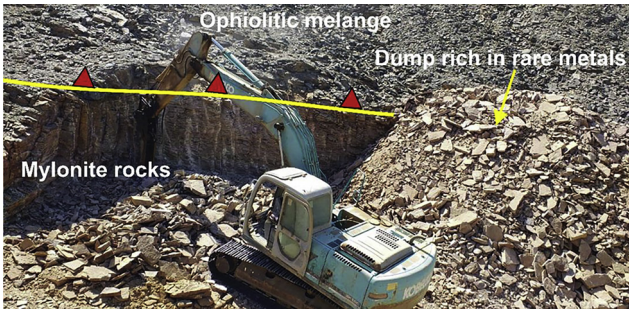

Fig. 3. Trench excavation at the contact between ophiolitic mélange and mylonitic rock, W. Abu Rusheid, looking S

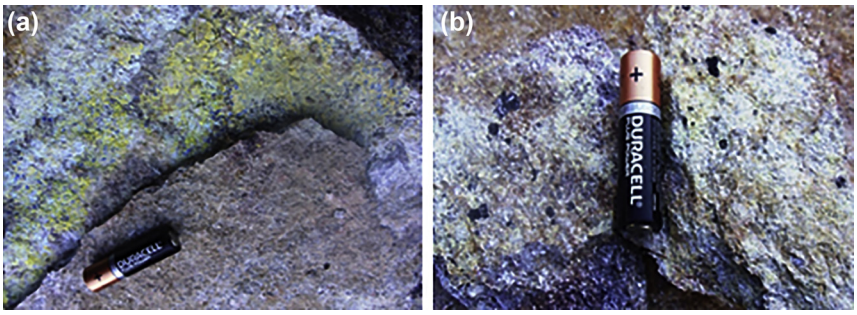

Fig. 2. (a)Visible yellow color kasolite in mylonitic rocks of Abu Rusheid area. (b) Visible black color columbite in mylonitic rocks of Abu Rusheid area

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size of the head sample to a top size of 1 mm. The comminution processes were carried out by using jaw crusher then Denver rod mill grinder. The ground product (−1,000 μm) was deslimed using a desliming cone to calculate the percentage of slimes. After that, the deslimed fraction was screened using a series of sieves beginning with 1,000 μm down to 45 μm to produce six size fractions (1000, 700, 500, 250, 125, 45 μm) that used as a feed for mineralogical investigation and physical upgrading operations.

For the mineralogical investigation of the studied sample, a representative comminuted samples (weighing about 50 g) from each size fraction as well as unsieved representative bulk sample are subjected to heavy liquid separation operations by first using bromoform (specific gravity = 2.89), then methylene iodide (specific gravity = 3.3) for calculating the total heavy mineral content (heavy bromoform fraction), light gangue silicates content (light bromoform fraction), mica content (light methylene fraction), and heavy economic polymetallic minerals content (heavy methylene fraction) for the bulk sample and also for each size fraction. Heavy and light products were washed with acetone then dried, and finally weighed to calculate their percent. From the obtained heavy fractions, pure mineral grains were hand selected with the aid of a binocular microscope, and then subjected to scanning electron microscope (SEM) in order to determine their mineralogical composition. SEM is equipped with energy-dispersive spectrometer (EDS) unit (Philips XL 30). The measurement conditions were an accelerating voltage of 30 kV with a beam diameter of 1 μm for a counting time of 60–120 s and a minimum detectable weight concentration ranging from 0.1 to 1 wt%.

Physical separation treatment for Abu Rusheid mylonite sample was first performed using magnetic separator equipment as Carpco dry high intensity magnetic separator (DHIMS) Model MIH (13) III-5 that is used to disjoin the paramagnetic minerals (magnetic fraction) from the diamagnetic minerals (non-magnetic fraction). The magnetic fraction was subjected to flotation separation experiments for separating muscovite from the associated polymetallic paramagnetic minerals using microflotation cell. Finally, the non-magnetic fractions were subjected to wet-gravity separator equipment as Wilfley shaking table (No. 13) to attain a concentrate of heavy non-magnetic minerals and eliminate the associated light gangue silicate minerals as much as possible.

All final processed fractions were confirmed by analyzing with X-ray diffraction (XRD) technique using Bruker Ds Discover X-Ray Diffractrometer. Diffraction patterns were recorded with a copper K-alpha X-ray source at a voltage of 40 kV and a 40 mA power (= 1.541 Å). The diffractometer was used in reflection mode. The data was collected at 0.05° (2θ) resolution, from 5 to 80° (2θ).

4. RESULTS AND DISCUSSION

4.1. Sample Preparation and heavy liquid separation

Grain size distribution analysis results of Abu Rusheid feed sample as well as the cumulative percent passing is depicted in Table 1 and Fig. 4. It is seen that the d_{80} and d_{50} of the sample are 0.75 mm and 0.35 mm respectively. Data of Table 1 and Fig. 4. proved that the comminution process was successful in keeping most of the feed sample weight (83.7%) within the operation size fraction (−1.00 + 0.045 mm) and reducing fines (−45 μm) as much as possible.

Table 1 also displayed the results of total heavy mineral content in the studied sample (sp. gr. more than 2.89), assay of mica (sp. gr. between 2.89 and 3.3) and assay of polymetallic minerals (sp. gr. more than 3.3) in relation with the various size fractions. Table 1 explicated that the comminution processes were saved 90.33% from the original total heavy mineral content within 83.7% by mass within the operation size. These results revealed that assay of the total heavy mineral ranges between 10.14 and 27.67% mass in different size fractions while in the bulk sample is represented as 19.25. The percentage of muscovite in different sizes ranges between 8.03 and 25.24%, while in the bulk sample it is 16.6%. The economic polymetallic minerals content ranges between 1.18 and 5.11% mass and in the bulk sample it represents 16.6% mass.

Microscopic examination of heavy liquids separation products revealed that Abu Rusheid sample is mainly composed of quartz and feldspar which make about 72.14% by mass and it also contains high percentage of muscovite, which represented about 16.6% by mass. The content of polymetallic minerals of the studied sample is about 2.65%

Table 1. Granulometric analyses and assay of total heavy, muscovite and polymetallic minerals among the various size fractions of Abu Rusheid mylonitic rocks

Size (μm)	Mass (%)	Cumulative (%) Passing	Total heavy Assay (%)	Muscovite Assay (%)	Polymetallic Assay (%)
−1,000 +700	24.58	100	10.14	8.96	1.18
−700 +500	14.97	75.42	16.24	14.58	1.66
−500 +250	22.64	60.45	27.67	25.24	2.43
−250 +125	14.00	37.81	26.12	22.39	3.73
−125 +45	7.51	23.81	13.14	8.03	5.11
−45 mm	7.69	16.3	9.67	5.91	3.76
Slimes	8.61	8.61	0	0	0
Original	100	0	19.25	16.6	2.65

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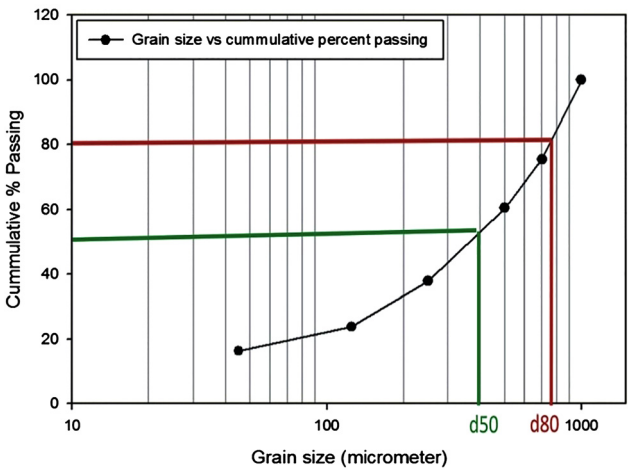

Fig. 4. Grain size distribution analyses of Abu Rusheid mylonitic sample

by mass and finally the percent of slimes about 8.61% by mass. Figure 5. shows the distribution of total heavy minerals, muscovite, and polymetallic minerals against grain size analyses. It proves that about 73.4% by mass of total heavy minerals distributed under 0.5 mm while 78.5% by mass polymetallic minerals distributed under 0.5 mm, Therefore, physical beneficiation processes will be influential in concentrating and upgrading the target minerals that present in the sample under investigation.

4.2. Mineralogical investigation

4.2.1. Base metals minerals. Cassiterite (tinstone) is the main source of tin all over the world. The mineralogical examination of Abu Rusheid cassiterite revealed that cassiterite is brown to black color and occurs as large anhedral crystals. Backscattered-electron (BSE) image and energy dispersive X-ray spectroscopy (EDX) spectrum of

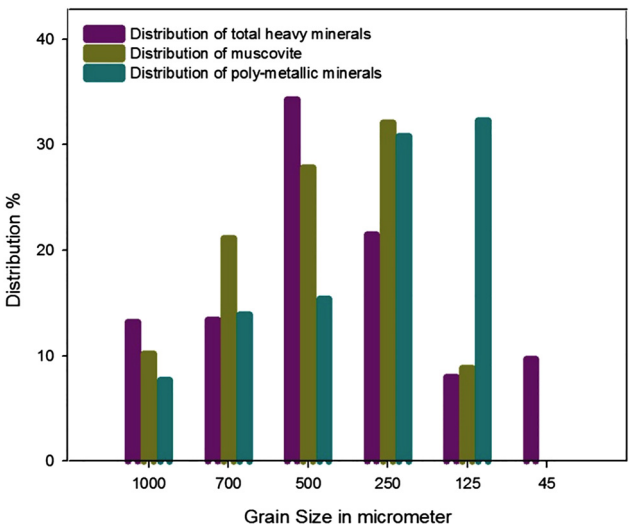

Fig. 5. Distribution of total heavy minerals, muscovite and poly-metallic minerals of Abu Rusheid sample

cassiterite grain are displayed at Fig. 6a. The semi-quantitative chemical analysis data reflected that SnO_2 represented 100% by mass of cassiterite composition.

Brass is a copper zinc alloy mineral that can be originated from partial oxidation of base metal ore bodies containing copper and zinc sulfides. The studied brass has a brassy yellow color, metallic luster, malleable tenacity and found as tiny grains distributed in the fine fractions. BSE image for numeral studied brass grains were displayed in Fig. 6b and EDX data showed that the mineral is mainly composed of copper, zinc and Ni with deficient amounts of Fe, Ca, Cl, Si, and Al.

Chalcocite is considered as an important copper ore mineral and the most profitable copper ores, this is due to its high copper content and the ease with which copper can be separated from sulfur. Abu Rusheid chalcocite grains are opaque and dark-gray to black color with a metallic luster. They distribute at different grain size classes especially less than 0.5 mm. BSE image and EDX data of chalcocite grains are presented in Fig. 6c. The semi-quantitative chemical analysis data for chalcocite reflected that it contains a high percentage of copper.

Linarite is an important primary ore mineral as source for lead and copper. Abu Rusheid linarite has bright azure color and distributed in fine size fractions. BSE image and EDX data of Abu Rusheid linarite grains (Fig. 6d) show that the mineral is enriched in lead and copper.

4.2.2. Rare metal minerals. Columbite (niobite) is the niobium-rich final member of the columbite-tantalite solid solution series. Abu Rusheid columbite grains have black color and a brilliant metallic luster. Both of ferro- and mangano-columbite grains were detected in the studied sample BSE images and EDX spectra of the investigated ferro- and mangano-columbite are showed in Fig. 7a and b respectively.

Titanite [$CaTiSiO_5$] grains of Abu Rusheid sample have brownish yellow color and present as dense translucent with form of anhedral to subhedral. They have a characteristic resinous luster. BSE image and EDX spectrum of the studied titanite grain is represented at Fig. 7c.

Tourmaline is a ring-structured borosilicate mineral, rich in aluminum, iron, magnesium, sodium, and lithium of trigonal crystal system. BSE image and EDX analyses of the studied tourmaline grains are represented at Fig. 7d.

4.2.3. Radioactive minerals. Kasolite is a distinguishable mineral because it considered as the only known uranyl silicate mineral bearing lead. Abu Rusheid kasolite is present as gathered crystals with lath-like to needle-like shape as shown in BSE image (Fig. 8a), has canary yellow color and characterized by its softness to crushing so it is distributed in fine size fractions. EDX spectrum data of the studied kasolite was presented at Fig. 8a and confirmed that kasolite is mainly composed of lead, uranium and silicon.

Monazite is a rare earth phosphate mineral, composed essentially of light rare earths phosphate. Abu Rusheid monazite grains were manifested and distributed in most of

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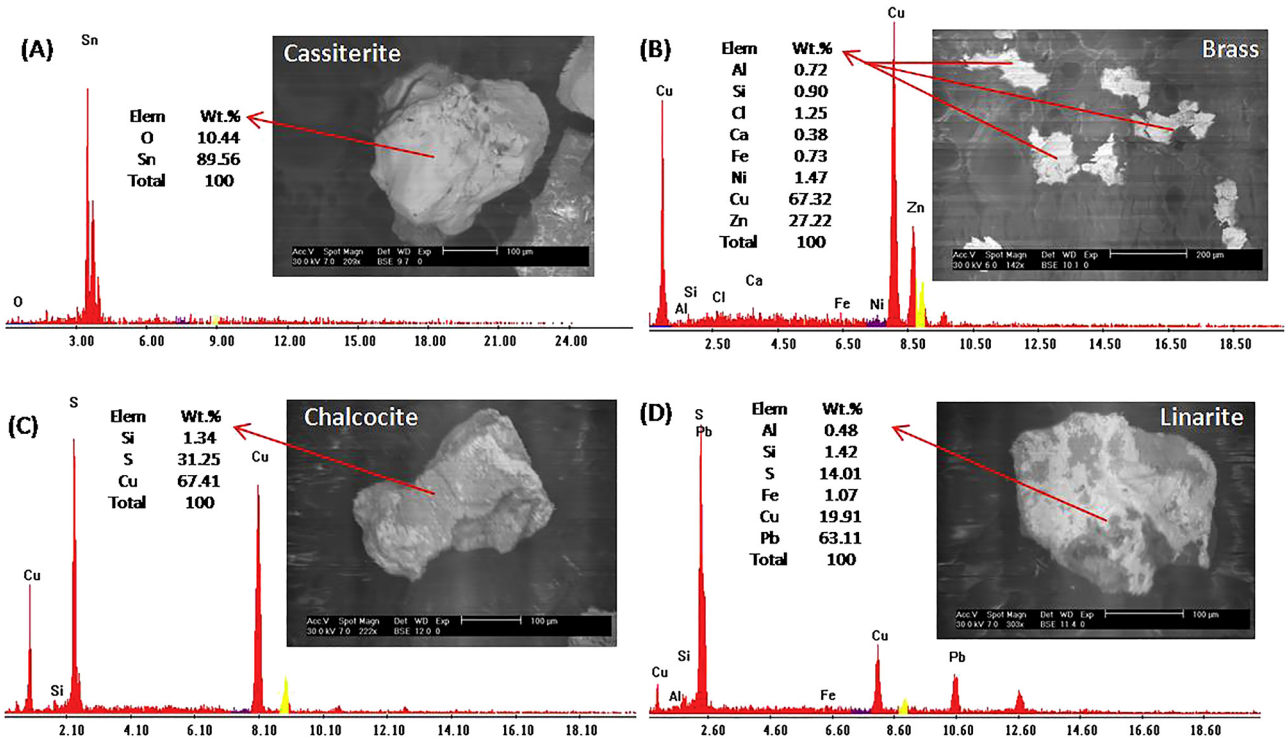

Fig. 6. BSE images and EDX spectra of base metal minerals of Abu Rusheid sample; (A) Cassiterite, (B) Brass, (C) Chalcocite, and (D) Linarite

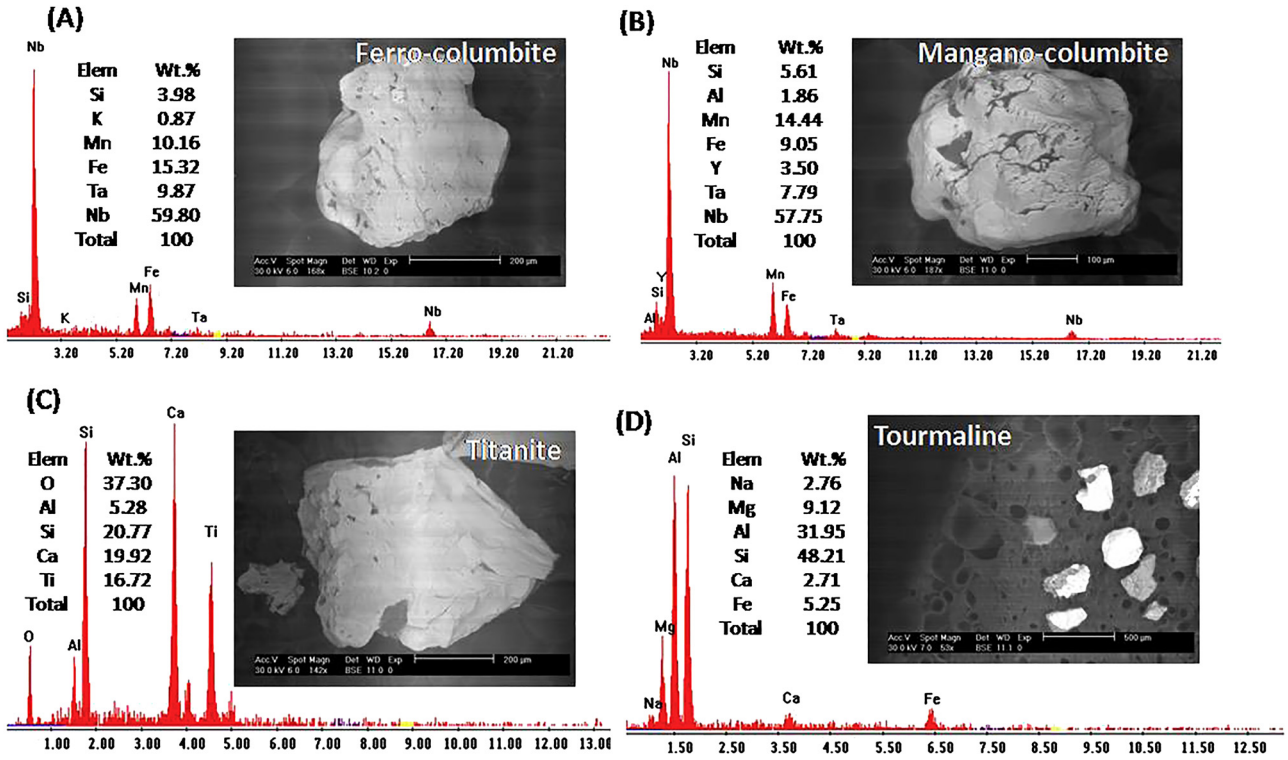

Fig. 7. BSE images and EDX spectra of rare-metal minerals of Abu Rusheid sample; (A) Ferrocolumbite, (B) Manganocolumbite, (C) Titanite, and (D) Tourmaline

size classes from 1 to 0.045 mm. Abu Rusheid monazite crystals are massive of anhedral to subhedral with granular form and having a characteristic vitreous or resinous luster. Also, monazite crystals are translucent, compact, hard and reddish orange in color. BSE image and EDX spectrum of Abu Rusheid monazite grains are presented in Fig. 8b and

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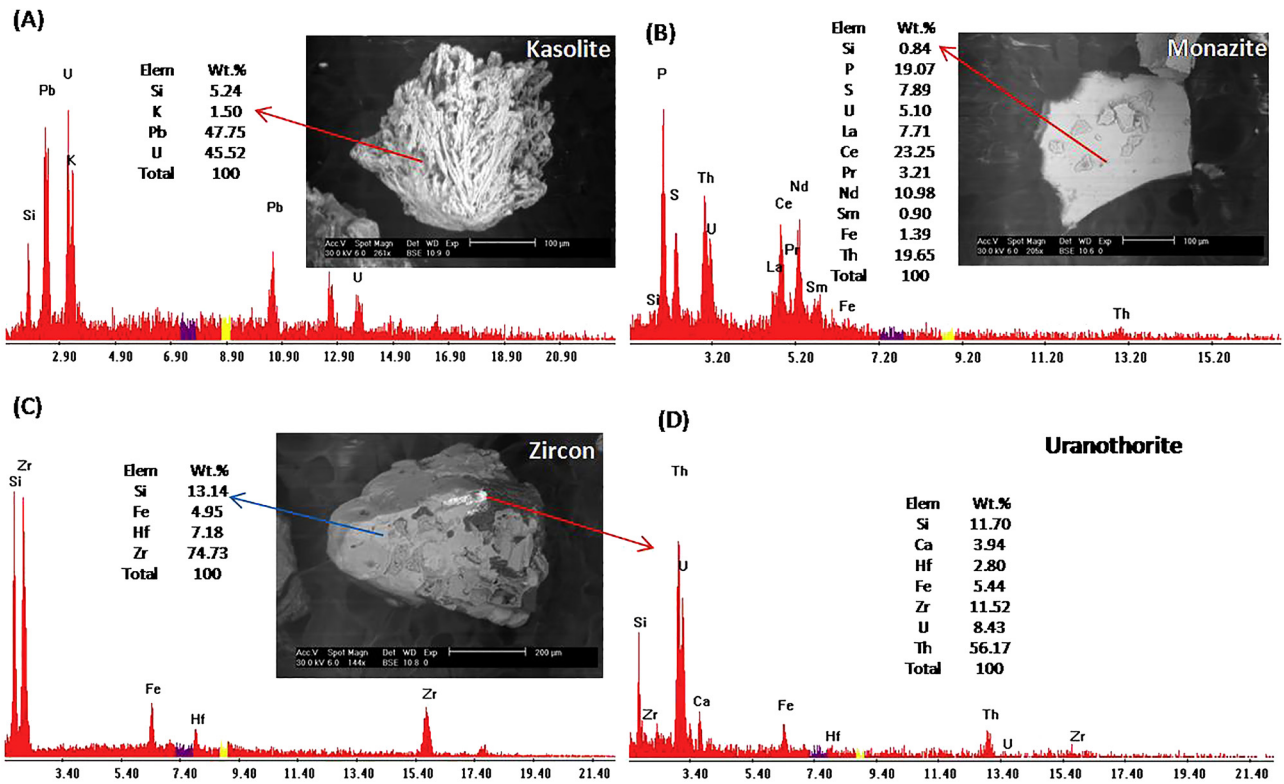

Fig. 8. BSE images and EDX spectra of radioactive minerals of Abu Rusheid sample; (A) Kasolite, (B) Monazite, (C) Zircon, and (D) Uranothorite inclusion

revealed that monazite grains are mainly composed of P, Ce, Th, Nd, and La. It also resulted that the most abundant light rare earth element is Ce while neodymium and lanthanum are the subsequent ones. On the other hand, quantities of U, Si, and S were identified at the studied monazite.

Zircon grains of Abu Rusheid sample are generally characterized by their coarse sizes, distributed in all size classes from 1 to 0.045 mm and have distinctive habit. Under a binocular microscope, they have pale to deep brown color and generally sub-translucent to opaque with dull luster. BSE image and EDX spectrum of zircon grains are presented in Fig. 8c. The semi-quantitative analyses of Abu Rusheid zircon grains revealed that zirconium and silicon are the dominant components.

Uranothorite grains were detected in Abu Rusheid sample with pale to dark yellow color and generally translucent to opaque. They occurred as gathered crystals of rounded to sub rounded or as granular form. Abu Rusheid uranothorite grains were distributed in the fine fractions (below 0.125 mm) and also found as numerous inclusions on zircon surface. BSE and EDX of uranothorite inclusion on zircon are presented in Fig. 8d. The semi-quantitative chemical analysis data reflected that the major elements of the uranothorite content are included Th, Si, and U. Also, minor amounts of Fe, Ca, Zr, and Hf were noticed as substitution in uranothorite crystal structure.

4.2.4. Sulfide minerals. Pyrite is the most common sulfide minerals. The studied pyrite grains have metallic luster brass-yellow color and distributed at all size classes. BSE image and EDX data of the studied galena were presented at Fig. 9a.

Arsenopyrite is an iron sulfoarsenide mineral and considered the most common ore of arsenic. Arsenopyrite grains are anhedral to subhedral, gray to silvery in color, have a metallic luster and distributed in all size fractions. SEM data of Abu Rusheid arsenopyrite was displayed at Fig. 9b.

Galena is a lead sulfide mineral and considered the most important ore of lead. Galena grains of Abu Rusheid sample have gray to silvery color, anhedral to subhedral and have a metallic luster. They are distributed in the fine size classes. BSE image and EDX spectrum of the studied galena were presented at Fig. 9c.

Molybdenite is the most common source of molybdenum and occurs in high temperature hydrothermal ore deposits. Microscopic examination of Abu Rusheid molybdenite grains revealed that they are black to silvery gray in color, subhedral to anhedral with metallic luster and distributed in the fine fractions. BSE and EDX of molybdenite were presented in Fig. 9d.

4.2.5. Fluorite. Fluorite shows large colorless to violet, subhedral to anhedral grains and distributed in the size range of 0.5–0.045 mm. BSE image and EDX data for Abu Rusheid fluorite grains indicated that fluorite has two modes of occurrence; the first one is normal fluorite grains without any inclusions while the other mode of occurrence

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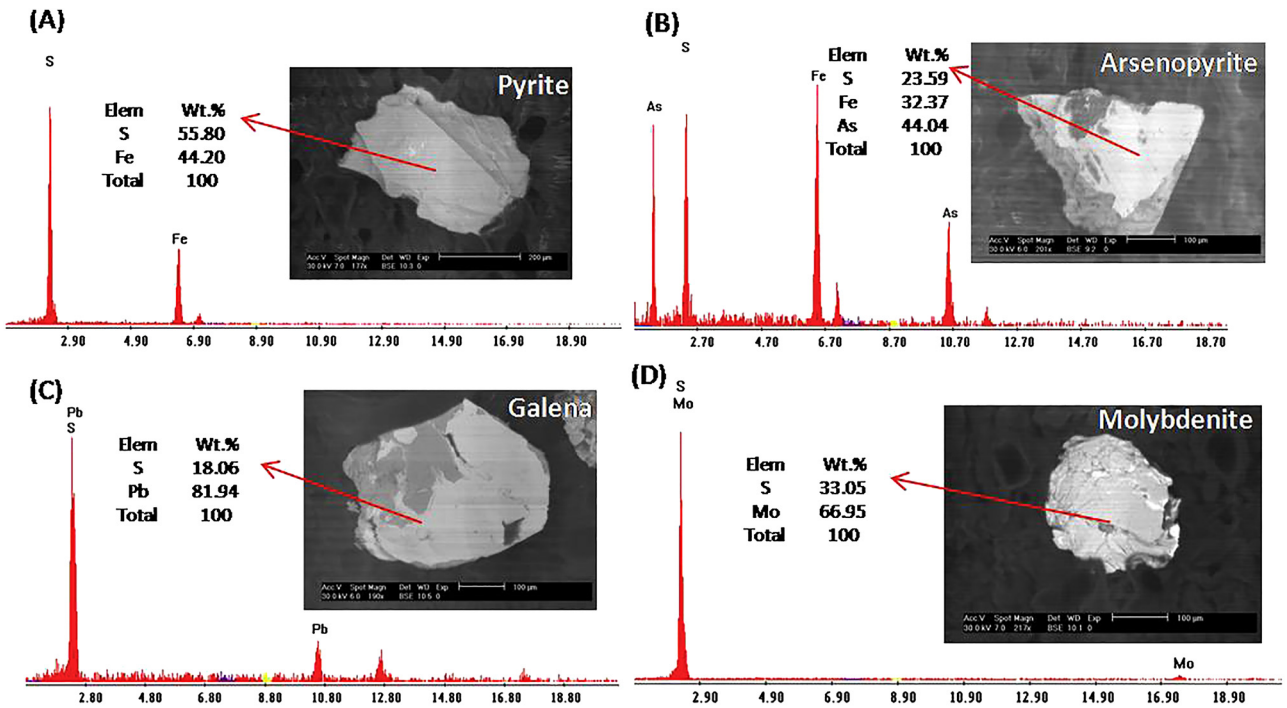

Fig. 9. BSE images and EDX spectra of sulfide minerals; (A) Pyrite, (B) Arsenopyrite, (C) Galena, and (D) Molybdenite

has numerous inclusions with different composition. BSE image and EDX data for fluorite and fluorite bearing inclusions were depicted at Fig. 10. Figure 10a showed the original fluorite grain which carries inclusions with mainly lead in composition (Fig. 10b) while other inclusion mainly U, Pb, Zn, and Cu (Fig. 10c). Figure 10d shows

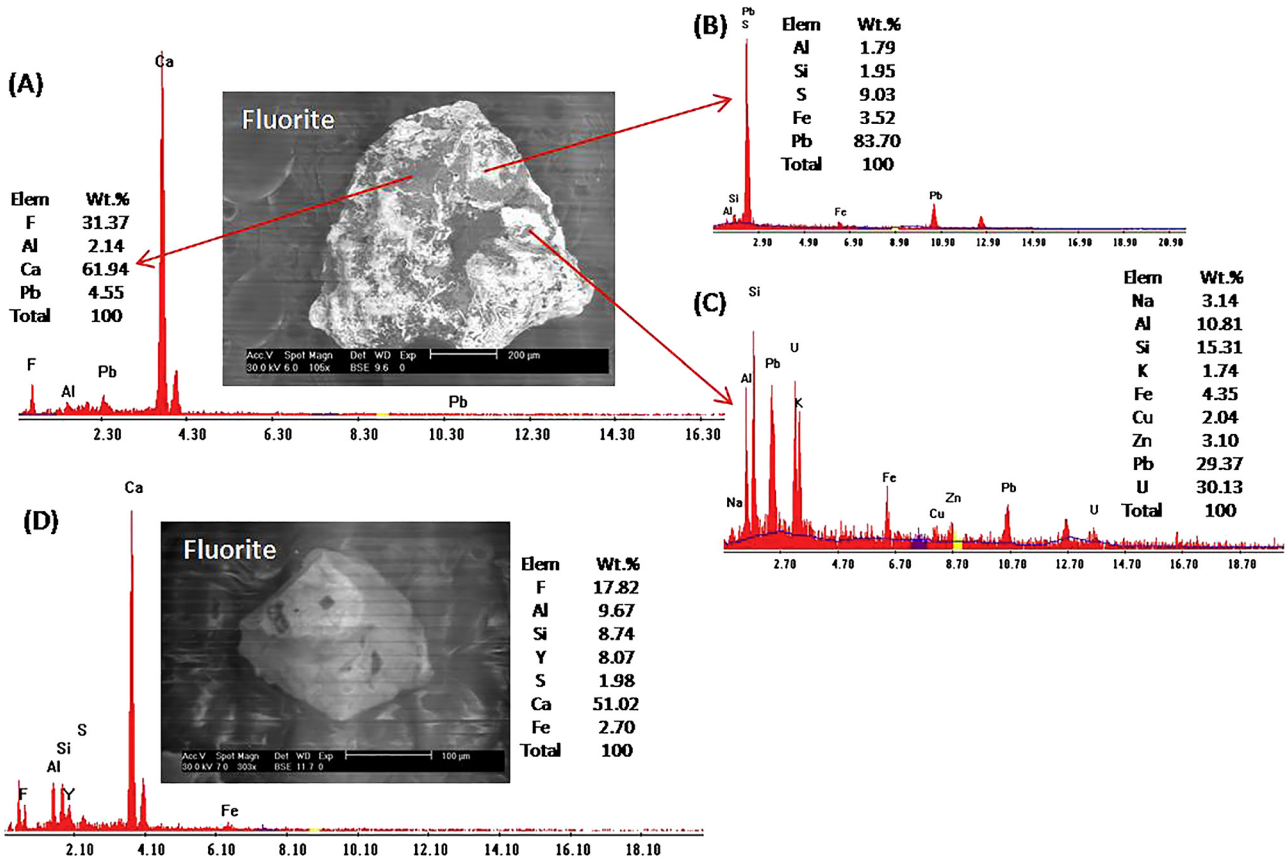

Fig. 10. BSE images and EDX spectra showing fluorite grains and their associations

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another fluorite grain but has yttrium and sulfur partial substitutions of Ca.

4.2.6. Iron oxide minerals (Jarosite). It is a hydrous sulfate mineral with potassium and iron; it is formed in the ore deposits by the oxidation of iron sulfides. The studied jarosite grains have yellowish to reddish brown color, translucent to opaque with a vitreous to dull luster, brittle, and distributed in all size fractions especially fine. BSE image and EDX data of the studied jarosite were displayed in Fig. 11d.

4.2.7. Muscovite. It represents about more than 16% of the total mass of studied Abu Rusheid sample. BSE image and EDX data analyses of the studied muscovite grains are represented at (Fig. 12). Semi-quantitative chemical analysis data reflected that muscovite is rich in iron and manganese content. Muscovite has received great attention due to its distinguishable properties as insulating and heat-resistant characteristics. Therefore, muscovite has several applications in the fabrication of coatings, paints, plastics, and electrical components [22].

4.3. Physical Processing

As a result of the mineralogical investigation of the studied sample, the mineralogical content was listed in Table 2 along with their specific gravities and magnetic properties. It showed that large group of minerals have high specific gravities which represents about 19.25% by mass (relative to light gangue minerals as quartz and feldspar which represent about 72.14% by mass) so they will easily respond to simple wet-gravity separation on a shaking table. On the other hand, other heavy minerals of the studied sample have some degree of paramagnetic behavior (monazite, brass, columbite, jarosite, hematite, and muscovite), so they are possible to separate them from the diamagnetic minerals (pyrite, arsenopyrite, galena, molybdenite, kasolite, zircon, uranothorite, cassiterite, chalcocite, titanite, tourmaline, fluorite) using DHIMS. High contents of muscovite was found in the studied sample (16.6% by mass) and make a problem through the wet-gravity separation, so it can be separated easily using flotation technique.

4.3.1. High Intensity magnetic separation. In order to separate paramagnetic minerals of the studied sample from the non-magnetic minerals (diamagnetic minerals), laboratory Carpco High-Intensity Magnetic Separator is used to achieve this goal and obtain a primary concentrate of the paramagnetic minerals (jarosite, muscovite, columbite, monazite, and brass). The paramagnetic mineral products were executed at a medium air gap between the surface of the rotor and the magnetized pole of 1.5 mm. The speed of roll and the feed rate were controlled at 50 rpm and 150 g/min respectively.

4.3.2. Floatability of muscovite. The paramagnetic fraction produced from magnetic separation was subjected to a

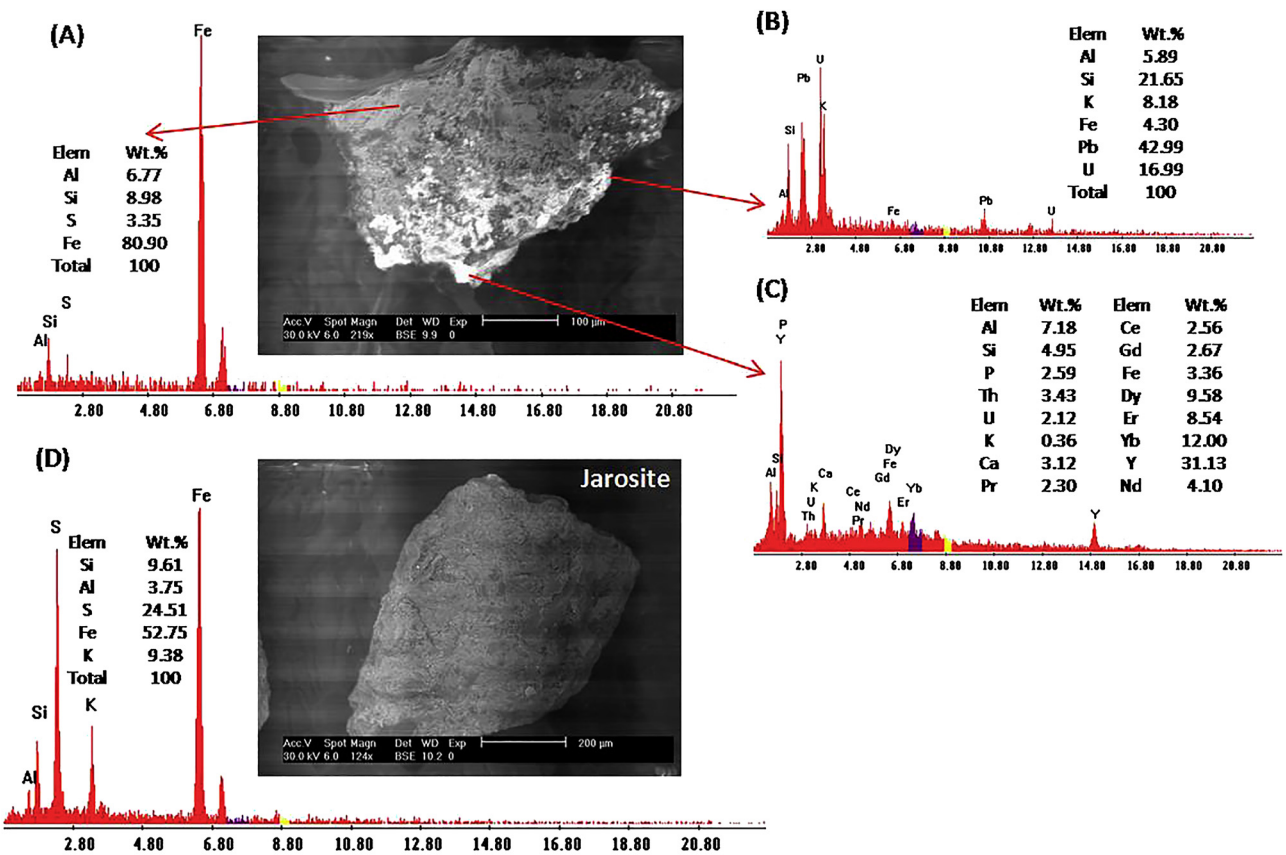

Fig. 11. BSE images and EDX spectra of iron oxide minerals bearing radioactive, REE, and base metals

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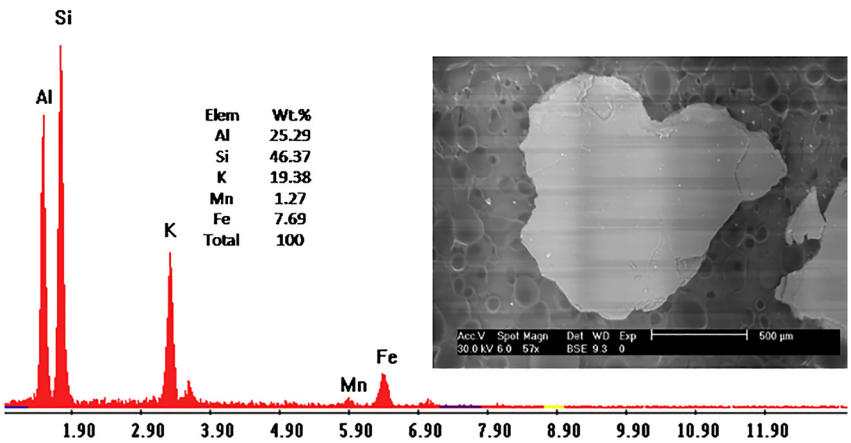

Fig. 12. BSE image and EDX spectrum of Abu Rusheid muscovite

Table 2. Abu Rusheid sample mineral content along with nominal specific gravity and magnetic property data

Abu Rusheid sample mineral content	Specific gravity	Magnetic properties
Quartz	2.63–2.65	Diamagnetic
Feldspar	2.5–2.6	Diamagnetic
Muscovite	2.8–3.1	Paramagnetic
Pyrite	5.10	Diamagnetic
Arsenopyrite	5.9–6.2	Diamagnetic
Galena	7.2–7.6	Diamagnetic
Molybdenite	4.73	Diamagnetic
Kasolite	5.8–6.5	Diamagnetic
Monazite	4.4–5.4	Paramagnetic
Zircon	4.5–4.7	Diamagnetic
Uranothorite	6.6–7.2	Diamagnetic
Cassiterite	6.90	Diamagnetic
Brass	8.4–8.7	Paramagnetic
Chalcocite	5.5–5.8	Diamagnetic
Linarite	5.35	Diamagnetic
Columbite	5–5.3	Paramagnetic
Titanite	3.53	Diamagnetic
Tourmaline	3–3.3	Diamagnetic
Fluorite	3.18	Diamagnetic
Jarosite	2.9–3.3	Paramagnetic
Hematite	3.55	Paramagnetic

flotation process for separating muscovite from the associated paramagnetic minerals. Magnetic product was initially ground as flotation feed was carried out on the size of less than 45 µm. The small scale flotation experiments were conducted in a micro-flotation cell and were carried out using purified individual muscovite firstly to investigate their flotation behavior in different conditions. Effects of collector concentration and pH were evaluated initially and then optimum conditions obtained were tested on magnetic product to float muscovite and depress the other paramagnetic associated minerals. Dodecylamine was used as collector while sodium hydroxide and sulfuric acid were used as a pH modifier. Pine oil was used as frother. It is evident that the flotation recoveries of muscovite using dodecylamine is well above 90% with optimum conditions of 1×10^{-4} mol/L of dodecylamine as well as pine oil at pH value of 2 and −45 µm grain size.

Both products of flotation process float and sink were identified using XRD technique and the data obtained was presented in Figs 13 and 14 respectively. The diffraction

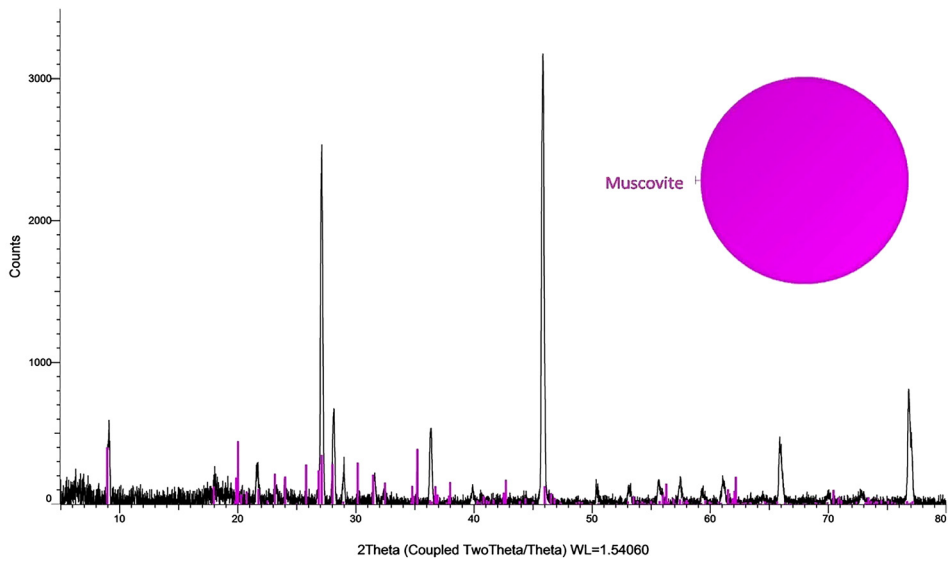

Fig. 13. X-ray diffraction pattern for float muscovite product of Abu Rusheid sample

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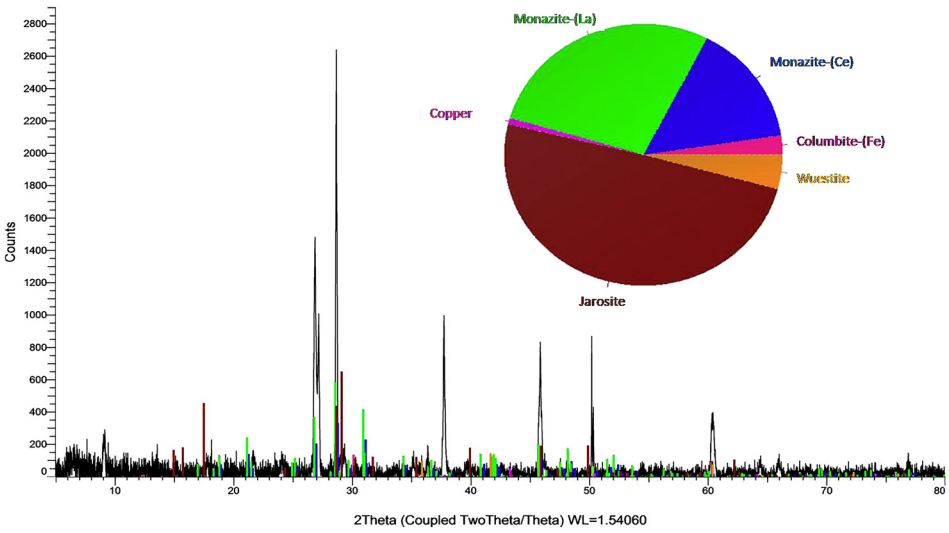

Fig. 14. X-ray diffraction pattern for sink polymetallic minerals product of flotation process, for Abu Rusheid sample

lines of the float product are in accordance with crystallography open database (COD) card no. 9006328 for muscovite, while the diffraction lines of the sink product are in accordance with COD card no. 9015174 for ferrocolumbite, COD card no. 9001646 for monazite-(Ce), COD card no. 9001647 for monazite-(La), COD card no. 5000216 for copper, COD card no. 9010441 for jarosite and COD card no. 1011169 for wuestite.

4.3.3. Wet-gravity concentration. To obtain clean concentrate of heavy non-magnetic minerals as zircon, kasolite, cassiterite, titanite, fluorite, uranothorite, and sulfide minerals and separate them from the associated gangue silicates non-magnetic minerals as quartz and feldspar, a wet-gravity separation process using Wilfley shaking table was carried out to obtain a secondary concentrate of heavy non-magnetic mineral. The pre-controlled conditions of this process were optimized by using a feed rate of 5 kg/h, water flow rate of 4 L/min, stroke length of 10 mm and table inclination of 8°. The obtained heavy non-magnetic concentrate and light non-magnetic gangue tail were identified using XRD and presented in Figs 15 and 16 respectively. The diffraction lines of the heavy non-magnetic concentrate are in accordance with COD card no. 1011265 for zircon, COD card no. 9004093 for costibite, COD card no. 9011848 for kasolite and COD card no. 9000001 for galena. While the diffraction lines of the light non-magnetic gangue minerals are in accordance with COD card no. 9015022 for quartz, COD card no. 9000161 for orthoclase, COD card no. 9000783 for albite, COD card no. 1000034 for anorthite and COD card no. 9000748 for labradorite.

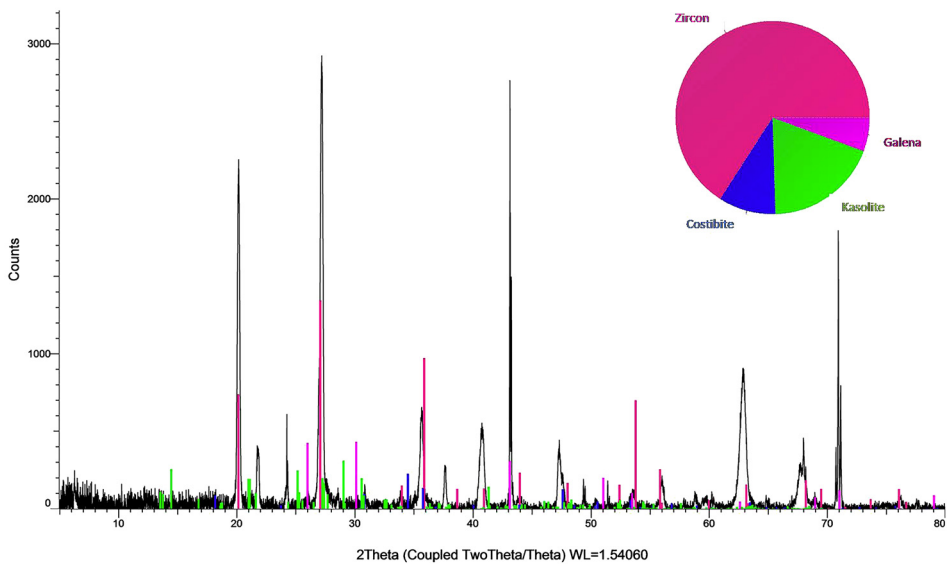

Fig. 15. X-ray diffraction pattern for heavy non-magnetic polymetallic minerals product of wet-gravity concentration process for Abu Rusheid sample

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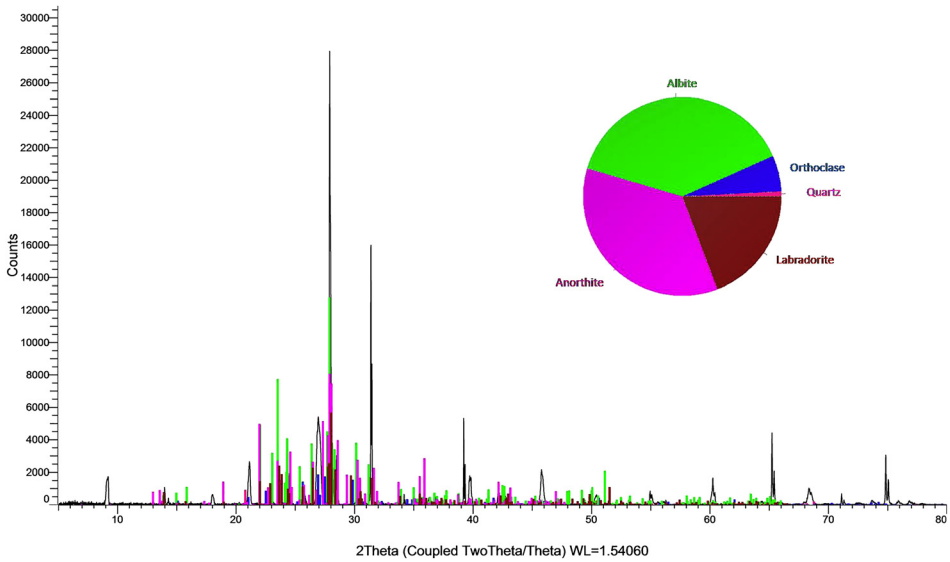

Fig. 16. X-ray diffraction pattern for light gangue minerals as products of wet-gravity concentration process for Abu Rusheid sample

A schematic sequence of the processes followed in the upgrading operations of the Abu Rusheid sample is presented in the form of a proposed flow sheet in Fig. 17.

5. CONCLUSIONS

Abu Rusheid area is considered one of the promising areas, as it contains various polymetallic minerals of great importance. As results of the mineralogical investigation of this study, the content of the polymetallic minerals of Abu Rusheid mylonitic sample is about 2.65% by mass and the content of the main associated gangue minerals (quartz and feldspar) is about 72.14% mass and it also contains high percentage of muscovite. Microscopic investigation using XRD and SEM analyses confirmed the occurrence of several industrial, economic and strategic polymetallic minerals like columbite, cassiterite, pyrite, arsenopyrite, molybdenite,

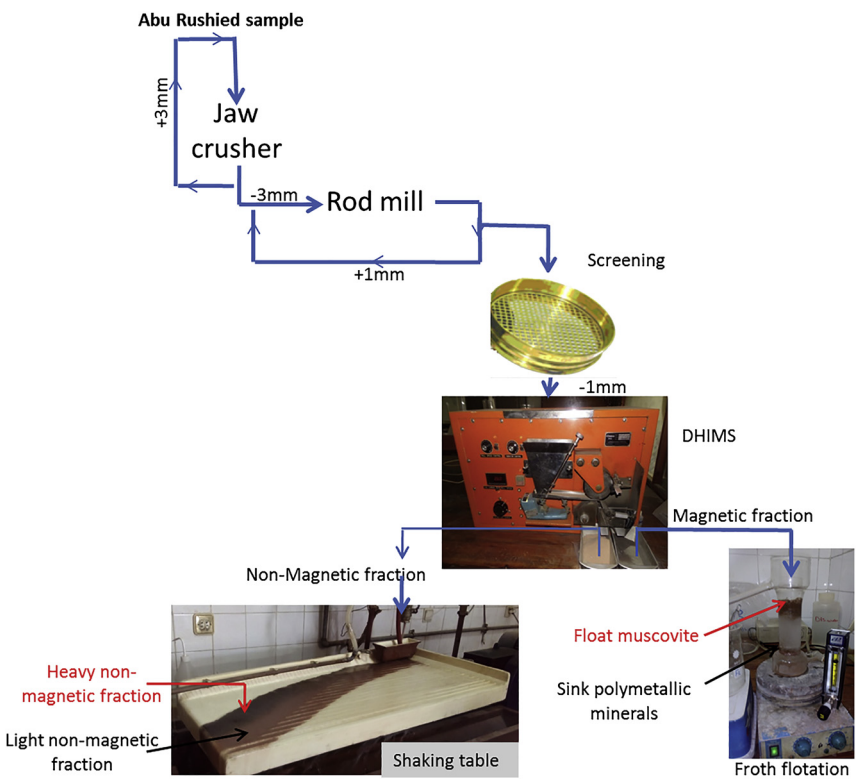

Fig. 17. Preliminary process flow-sheet proposed for separation of valuable polymetallic minerals from Abu Rusheid sample

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galena, monazite, zircon, uranothorite, titanite, fluorite, and brass. The distribution of total heavy minerals against grain size analyses proves that about 73.4% by mass of total heavy minerals distributed under 0.5 mm while 78.5% by mass polymetallic minerals distributed under 0.5 mm, so physical beneficiation processes will have an effect by using simple gravity separation technique on a shaking table for rejection of quartz and feldspar as light gangue and upgrade the heavy mineral contents and also dry high intensity magnetic separation will be suitable for separating paramagnetic from diamagnetic minerals.

Recovery of the economic content minerals from Abu Rusheid mylonitic sample using magnetic separation, wet-gravity separation (shaking table), and flotation technique was successfully achieved. Three different types of concentrates were obtained; heavy paramagnetic concentrate, heavy diamagnetic concentrate and muscovite concentrate.

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