

# Detecting Mineral Resources and Suggesting a Physical Concentration Flowsheet for Economic Minerals at the Northern Border Region of Saudi Arabia

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Received: 8 March 2022 | Revised: 28 March 2022 | Accepted: 5 April 2022

**Abstract**-There is a limited number of studies on sand deposit resources of Saudi Arabia, which cover nearly the one-third of the area of the country, whereas most of these studies deal with the environmental rather than the mineralogical or mining aspects. In this paper, and in the effort to detect the mineral resources of the Northern Border Region, the surficial Wadi sediments along the Ar'ar-Sakaka road are studied. The deposits of several Wadies (Al Aqra, Shibban al Hanzaliyat, and Arar) are mixed. The sediments of the collected samples are investigated to determine definite areas characterized by a relatively higher content of heavy minerals and a relatively lower content of carbonate minerals that are also friable enough to be investigated by some of the available physical concentration techniques. A large quantity of the surficial deposits, weighing 4.69 tons was collected from the stretch at the investigated area which is 3km long and 1.5km wide. Evaluation of the heavy minerals content, their types, and their ability for concentration and separation, was conducted. A suggested physical concentration flowsheet was concluded for concentrating and separating the contained economic minerals. The average heavy mineral content is 1.55 wt% and the identified economic minerals are magnetite, ilmenite, hematite, goethite, zircon, rutile, anatase, monazite, and xenotime. The other contained heavy minerals include monoclinic pyroxenes (diopside, and augite), monoclinic amphibole (winchite), and muscovite mica. Dolomite and calcite carbonate are also contained. The concluding results ensure that magnetite, zircon, TiO<sub>2</sub> minerals, and monazite are mineable for separation in individual mineral concentrates. Most of the detected economic minerals are recorded in the area for the first time. Monazite, xenotime, and zircon are responsible for some recorded radioactivity in the area.

**Keywords**-wet gravity concentration; high intensity magnetic separation; heavy liquid separation; X-ray diffraction; scanning electron microscope

## I. INTRODUCTION

The sedimentary cover of the Kingdom of Saudi Arabia contains many resources of economic importance such as phosphorous and aluminum. The Precambrian rocks of Saudi Arabia are highly dissected by dry valleys that are filled by a wide variety of stream sediments. A thorough survey of the relevant literature indicates that there are no published studies on the economics of stream deposits in Saudi Arabia except for construction materials [1]. Transported (allochthonous) sediments of economic interest are usually referred to by geologist as placer deposits. The fluvial process (river transport) is effective in liberating and transporting gold as well as many heavy minerals and may concentrate them to economic grade [2-4]. Wadi Arar is one of several main Wadies in the Northern Border Region of Saudi Arabia [5]. The mineralogical investigation of the surficial sediments of Wadi Arar reflects the occurrence of some important economic minerals of iron and titanium. In fact, most of friable sand sediments, either placer beach sand, placer sand dunes, stream or wadi sediments, are sources of various economic minerals.

It is important to detect the mineral resources of the Northern Border Region, which is a wide area of almost 112,000km<sup>2</sup>. The investigation will start by covering the deposits along the area located to the right of the high way between Arar and Sakaka. At the end of this area, the deposits

of several Wadies (Al Aqra, Shibana al Hanzaliyat and Arar Wadies) are met and mixed. Therefore, relatively larger amounts of sediments are noticed in the area. However, the amount of materials transported from each Wadi may depend on several variables such as the flow type and the sediment load [6]. Hence, the occurrence of various heavy minerals is expected and some of them may be of economic interest. The determination of the types and contents of the associated economic minerals of these deposits and their mineability for some physical concentration techniques are the main subject of the current study.

## II. STUDIED AREA AND SAMPLING TECHNIQUES

### A. The Studied Area

The studied area consists of friable sediments, mainly sand, carbonates, and silt. It is located to the right along the high way between Arar and Sakaka, 12km from Arar, Northern Border Region, until 10km before Talat Ammar, Al Gouf Region, a distance of about 40km. Twenty two samples were taken from the top surficial meter of the deposits along a perpendicular profile, in a distance of 250m to the right of the high way. One sample was taken for each two successive kilometers. Also, about 4.69 tons of the surficial friable sediments were collected from the area located 14km before Talaat Ammar and extending towards Sakaka. The area is about 3km along the high way and has a width of 1.5km to the right of the road (Figure 1). The average depth of the taken sediments ranges between 20 and 30cm.

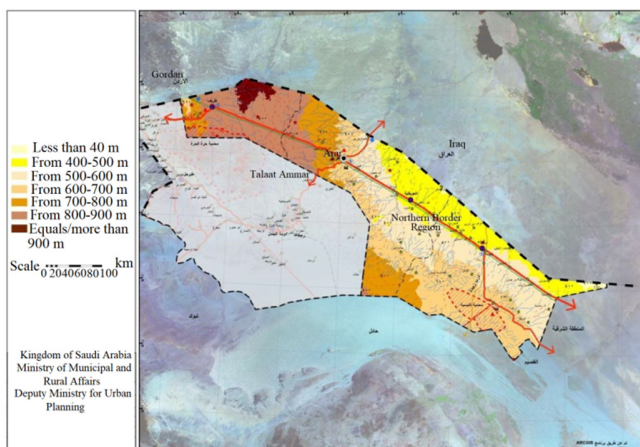


Fig. 1. The Northern Border Region and the location of the studied area, at the right of the road from Arar to Talaat Ammar.

### B. Sampling Techniques

Several techniques and instruments were used in the mineralogical investigation and the physical concentration of the collected samples. They include the following:

- An oven for drying.
- Screening using a 2mm and/or 500 $\mu$  size aperture screen to remove trash and/or large sediment fragments.
- A Jones riffle splitter to obtain representative samples of various weights.

- A mechanical shaker and a set of standard sieves, with size apertures of 50, 3, 2, 1, 0.5, 0.25, 0.125, 0.063, and 0.045mm, at a definite adjustment of operating conditions to study the size distribution of the collected samples.
- Heavy liquid separation technique using bromoform (with 2.89gm/cm<sup>3</sup> density), separating funnels, glass funnels, fast filtration papers, glass rods, holders, and acetone.
- A binocular microscope for investigating the mineral components of the various samples and also for counting the detected heavy mineral grains.
- The Outotec laboratory high intensity induced roll magnetic separator, Model: MIH (13) 111-5 PHYSEP-INC USA for the differentiation of the different heavy and economic minerals into magnetic and non-magnetic mineral fractions. The separator is adjusted at definite parameters of operating conditions: air gab, feeding rate, rotor speed, and definite splitter position adjustment between the two obtained magnetic and non-magnetic fractions, using definite ampere values.
- A half-size shaking table to investigate the wet gravity concentration of the various economic and heavy minerals at a definite adjustment of operating conditions of feeding rate, feeding pulp density, washing water, and stroke frequency. The recommended deck side slope is in the range of 8-12mm/m and the stroke length is 16mm.
- X-Ray Diffraction (XRD): Philips X-ray generator (PW 3710/31) with automatic sample changer (PW 1775, 21 position) using scintillation counter, Cu-target tube and Ni filter at 40kV and 30mA was used. This instrument is connected with a computer system using the X40 diffraction program and ASTM cards for mineral identification.
- The Environmental Scanning Electron Microscope (ESEM): Highly purified picked mineral grains representing the different heavy minerals were examined by a Philips ESEM model XL 30 equipped with an energy dispersive X-ray unit (EDX). ESEM and EDX analyses were used to investigate the morphological and chemical characteristics of the examined mineral grains.

## III. THE IMPORTANCE OF TITANIUM AND ZIRCONIUM MINERALS

Ilmenite is mainly used for the manufacture of titanium dioxide white pigment which is the whitest of all white pigments known today. This pigment is more stable, being entirely unaffected by acids or alkalis that dissolve and destroy other whites. It has the good ability to maintain its visual appearance for a considerable period of time and is stable up to 1800°C. Rutile is mainly used in the manufacture of arc-welding electrodes, and for the production of titanium dioxide electrodes and is used as a coating material in ship-building and other structural steel for which there is a growing demand [7].

Titanium forms extremely hard metallic compounds with carbon, silicon, nitrogen, and boron. These are used as tips for cutting tools and in abrasive stones and wheels. Titanium

dioxide is used as an opacifier in porcelain enamels on steel sheet for refrigerators, sanitaryware, etc. Ceramic titanates are used in the electric industry. Ilmenite and rutile are now extensively used in the paint industry as well as in rubber, plastic, paper, textile, and ceramic industries [8-9].

The three principal zircon-based industries are refractories, foundries, and ceramics. Zircon sand is used in molds and shall cores, while it is becoming important to the foundry market. Due to its chemical inertness, good heat conductivity, high specific gravity, low expansion, good resistance to abrasion, high melting point, and size stability upon heating up to 1,750°C, zircon is an outstanding refractory mineral. Another traditional usage is in the ceramic industry, where the finely milled material is applied to glazes and its high refractive index is utilized to good effect for pacification purposes [10].

Zirconium offers excellent corrosion resistance and, consequently, is widely used in chemical process equipment, reactor vessels, and aerospace engineering. In particular, in the nuclear industry, zirconium in the form of zircaloy has yet to find a competitor as a cladding and structural material in water-cooled, pressurized, and boiling water type nuclear reactors [9].

#### IV. RESULTS AND DISCUSSION

##### A. Treatment of the Collected Samples

For each of the 22 collected samples, the used mineralogical analysis procedure program was:

- Drying of the collected individual samples at 110°C for 1h.
- Screening with a 2mm aperture screen to remove the oversize wt% (Table I).
- Each sample was split to obtain a relatively smaller representative sample of suitable weight.
- Using the relatively smaller representative sample, the slime wt% content was determined using the decantation method. The decantation was repeated several times until the decanted water became clear from any suspended particles. The residue of sediments was dried and weighed. The wt% of slime content was calculated (Table I).
- Each deslimed original sample was subjected to a process of wet gravity concentration to obtain a bulk first tabled concentrate containing most of the contained economic minerals and a considerable portion of other heavy minerals. The grade of the obtained bulk concentrate was low while the recovery for most of the individual economic minerals is very high. The obtained individual tabled concentrates of the treated 22 samples range between 5.6 and 22 wt% (Table I).
- Screening process with a 500 $\mu$  size aperture screen was carried out for each individual bulk tabled concentrate to remove some of the oversized calcareous fragments which can affect the feeding rate during the magnetic separation. The wt% of the obtained oversize fraction was calculated (Table I).
- For each obtained undersize fraction (-500 $\mu$ ), the process of magnetic separation was carried out using successive

current values of 0.05, 0.6, and 1.5A. The weight % for each obtained fraction was calculated (Table I).

- For each obtained individual non-magnetic fraction at 1.5A, wet gravity concentration process was carried out to obtain a second tabled concentrate for each sample. This fraction would contain most of zircon and TiO<sub>2</sub> minerals (rutile and anatase).
- For each obtained second tabled concentrate, the process of heavy liquid separation using bromoform (2.89g/cm<sup>3</sup>) was carried out.
- Mineral identification and counting: each of the obtained bromoform heavy liquid fractions was investigated under the microscope. A definite representative number of grains, ranging between 750 and 1,000, for each individual heavy fraction were detected and counted (Table I). The grain size of the mineral grains must be considered during the microscopic counting. The weight percent of each mineral in every fraction was calculated using the equation of [11].

Due to the investigation of several samples in Wadi Arar [5], it is known that magnetite is the essential economic mineral in the area, while ilmenite and goethite are considered minor ones. So, it is better to depend on the contents of magnetite, zircon, and rutile in evaluating the investigated samples. Hence, both the obtained magnetic fractions, at 0.05A which contains most of the magnetite content, and the non-magnetic fraction at 1.5A which contains most of zircon and rutile contents, can be used to choose the most suitable sediment region for carrying out the physical concentration experiments. However, both the other two magnetic fractions obtained at 0.6 and 1.5A are composed mainly of pyroxenes, amphiboles, and minor ilmenite, goethite and monazite. Then, the region at the end of the investigated area is considered to be the relatively more enriched with economic minerals (Table I). It also contains a relatively lower content of the calcareous fragments and the most friable sediment grains. This is why the relatively larger bulk sample was collected from this region.

##### B. The Physical Concentration of the Bulk Large Sample

For the collected larger sample of 4.69 tons, the following steps were carried out:

###### 1) Determination of the +2 mm Oversize Fraction

A representative sample of 2kg was taken from the collected bulk raw sediments. Screening was carried out for the sample using an aperture screen of 2mm. The trash oversize fraction was calculated as 1.93 wt%.

###### 2) Determination of the Grain Size Distribution

A considerable representative sample was taken from the obtained undersize fraction (-2mm) and was treated using the mechanical shaker and a set of sieves with screen aperture sizes of 1, 0.5, 0.25, 0.125, and 0.075mm. Taking into consideration the obtained +2mm oversize fraction into calculation, the various grain size classes are given in Table II.

TABLE I. DIFFERENT MINERALOGICAL TREATMENTS AND COMPONENTS OF THE INVESTIGATED COLLECTED RAW SAMPLES. M=MAGNETIC AND NM=NONMAGNETIC FRACTIONS, FR=FRACTION AND CONC.=CONCENTRATE

Sample	+2mm %	Slime %	First tabled tailing %	First tabled conc. %	Distribution of the magnetic fractions of the first tabled concentrate %					Distribution of the various obtained tabled fractions of the 1.5A nonmagnetic Fr %		Original heavy Frs	Original mineral composition contents of the heavy fractions, %			
					+500 $\mu$	0.05Am	0.6Am	1.5Am	1.5Am	Second tabled tailing	Second tabled conc.		Zircon	Rutile	Pyroxenes	Carbonates
1	7.7	2.1	68.2	22	5.46	0.41	1.15	1.59	13.39	11.10	2.3	0.103	0.046	0.026	0.025	0.006
2	23.9	5.8	60.4	9.9	2.82	0.08	0.66	1.07	5.26	3.94	1.3	0.057	0.027	0.012	0.014	0.004
3	15.1	1.7	72.5	10.7	3.90	0.24	0.37	0.46	5.73	4.57	1.2	0.049	0.023	0.010	0.010	0.005
4	8.5	2	79.2	10.3	3.22	0.32	0.48	0.49	5.80	4.39	1.4	0.064	0.032	0.013	0.015	0.004
5	15.3	0.9	76.3	7.5	1.95	0.39	0.51	0.41	4.25	3.71	0.5	0.016	0.006	0.003	0.004	0.003
6	13.5	1.7	76.8	8	1.74	0.20	0.32	0.44	5.29	4.16	1.1	0.032	0.015	0.007	0.006	0.004
7	32	1.3	54.8	11.9	5.09	0.18	0.35	0.53	5.75	4.53	1.2	0.053	0.023	0.011	0.016	0.003
8	2.3	1.8	82.9	13	2.27	0.39	0.63	0.50	9.21	6.95	2.3	0.097	0.048	0.029	0.014	0.006
9	19.6	1.5	70.9	8	2.54	0.29	0.44	0.42	4.31	3.54	0.8	0.021	0.011	0.004	0.003	0.002
10	8.5	1.4	81.6	8.5	2.24	0.36	0.51	0.49	4.90	3.63	1.3	0.036	0.017	0.008	0.009	0.003
11	4.5	0.7	82.1	12.7	3.58	0.30	0.49	0.62	7.71	5.78	1.9	0.064	0.023	0.011	0.022	0.008
12	3.7	1.4	81.9	13	2.56	0.40	0.59	0.68	8.78	6.64	2.1	0.069	0.035	0.018	0.014	0.003
13	8.2	1.6	78.2	12	1.58	0.33	0.56	0.61	8.91	6.56	2.4	0.071	0.035	0.014	0.015	0.006
14	10.3	1.2	76.6	11.9	3.10	0.45	0.79	0.77	6.78	5.36	1.4	0.053	0.028	0.010	0.011	0.003
15	5.6	1.9	81	11.5	3.08	0.38	0.59	0.51	6.95	5.04	1.9	0.117	0.052	0.024	0.033	0.007
16	1.8	2.2	87.5	8.5	2.18	0.33	0.46	0.43	5.11	4.14	1.0	0.078	0.035	0.016	0.023	0.004
17	2.6	1.8	84.9	10.7	2.38	0.33	0.55	0.55	6.91	5.01	1.9	0.136	0.061	0.027	0.036	0.012
18	0.8	1.5	84	13.7	2.47	0.70	1.19	0.96	8.38	6.54	1.8	0.143	0.071	0.019	0.043	0.010
19	0	1.8	90.3	7.9	1.82	0.35	0.61	0.55	4.56	3.65	0.9	0.100	0.055	0.020	0.017	0.007
20	5.1	1.9	82.1	10.9	2.16	0.40	0.65	0.60	7.09	5.80	1.3	0.085	0.045	0.018	0.017	0.005
21	0.1	1.6	92.7	5.6	1.82	0.20	0.29	0.28	3.00	2.50	0.5	0.044	0.021	0.009	0.011	0.003
22	11.2	1.7	78.4	8.7	2.19	0.25	0.46	0.41	5.39	4.54	0.8	0.079	0.040	0.016	0.016	0.008

### 3) Determination of Slime Content

A relatively smaller representative sample was taken from the obtained under-size fraction (-2mm) to determine the slime content (-63 $\mu$ ) of the investigated raw sediments. The process of decantation was carried out for the sample. The residue of sediments was dried and weighed. The calculated slime content is 2 wt% (Figure 2).

TABLE II. VARIOUS GRAIN SIZE CLASSES OF THE STUDIED RAW SEDIMENTS

Items	Grain size classes, mm	Distribution of grain size of raw sediments, wt%
1	+2	1.93
2	+1	0.34
3	+0.5	3.79
4	+0.25	34.81
5	+0.125	39.80
6	+0.075	14.68
7	-0.075	4.65
Total %		100

### 4) Heavy Mineral Separation with Bromoform Heavy Liquid

Several relatively smaller representative samples were taken from the obtained deslimed fraction. The process of heavy liquid separation using bromoform was carried out for 3 of these representative samples. Their weight ranged between 30 and 38g. The heavy mineral content was determined by

taking the average of the individually obtained heavy bromoform fractions. The determined heavy mineral content of the investigated original raw sediments is 1.55 wt%.

### 5) Wet Gravity Concentration

A representative technological sample weighing 1290kg was taken from the bulk collected raw sediments (Figure 3(1)) of the area under investigation. The undersize sediment fraction (-2mm sized grains) was subjected to a rougher wet gravity concentration using the shaking table. Several circuits of wet gravity concentration by shaking table were carried out (Figure 2).

#### a) Rougher Wet Gravity Concentration

Several authors explained the operation principles of shaking tables [12-15]. Several representative raw sand samples were treated individually at different feeding rates, feed pulp densities, and washing water. Each time, a definite sample weight of about 100kg was dried using sunlight and screened using a 2mm aperture screen to remove the oversize fraction (+2mm), and was then subjected to a rougher stage of wet gravity concentration by shaking table (Figure 3(2)). The feeding rate ranged between 80 and 140kg, the feed pulp density ranged between 10 and 19 wt% while the used washing water ranged between 1.4 and 3.2l/m.

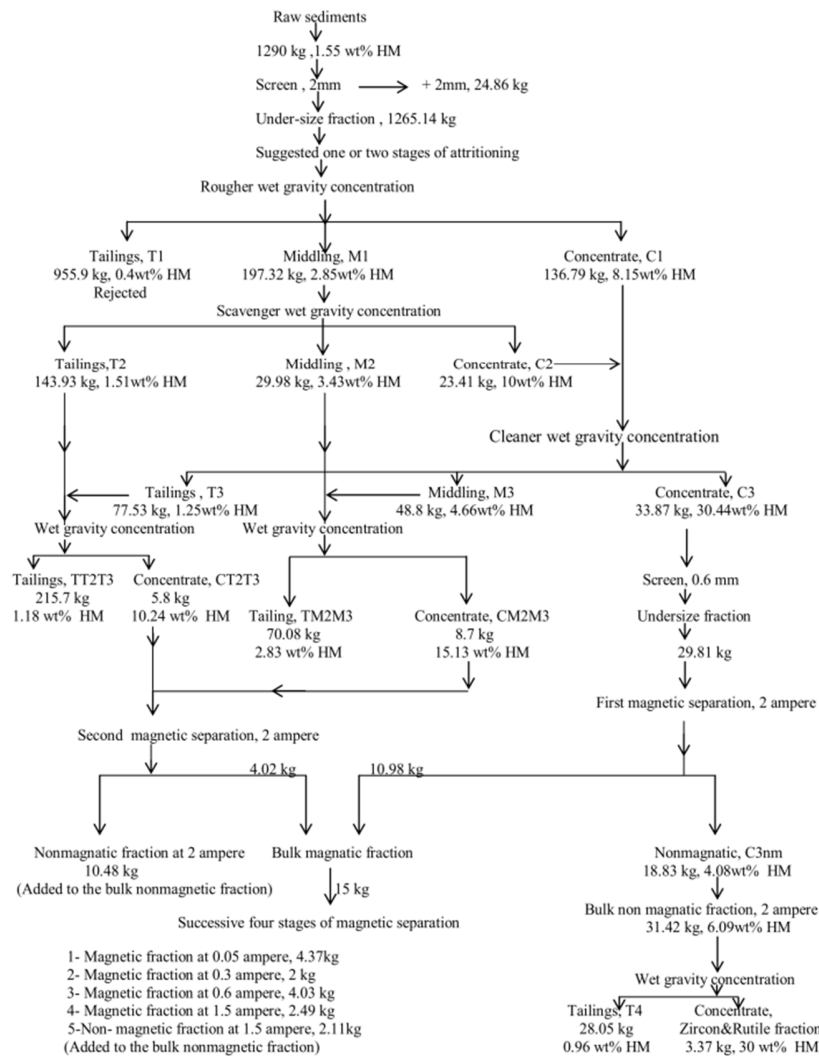


Fig. 2. A simplified flowsheet showing the different treatment stages of the studied sediments to obtain the various economic mineral concentrate fractions.

The following parameters represent the concluded optimum adjustment of operating conditions: feeding rate 100kg/h, feeding pulp density 14 wt%, washing water 2.2l/min, stroke length 12mm, and stroke frequency 300rpm, while suitable longitudinal and side slope values were used. The obtained rougher tabled concentrate (C1) weighs 136.79kg and contains 8.15 wt% heavy minerals (HM). The middling (M1) weighs 197.32kg and contains 2.85 HM. The tailings (T1) weighs 955.9kg, and contains 0.4 wt% HM (Table III). These three obtained tabled fractions represent 10.6, 15.3, and 74.1 wt% of the original raw sediments respectively. The obtained rougher tailings were discarded (Figure 2).

For a treated sample with feeding rate of 115kg/h, feed pulp density of 19 wt% and washing water of 1.4 l/min, the obtained tabled tailing (T1a) represents 78 wt% of the treated feed and contains 1 wt% heavy minerals. For another treated sample, with 140kg/h feeding rate, 11 wt% feed pulp density, and 3.1 l/min washing water, the obtained tailings (T1b) represent 81 wt% of the treated feed but contain 0.67 wt% HM. It is obvious that both the used feeding but rates and feed pulp densities are very

important in the recovery of the HM inside the tabled concentrate and lowering their loss in the tabled tailing fraction.

b) Cleaner Wet Gravity Concentration

The three shaking table parameters: feeding rate, feed pulp density, and washing water were recorded to obtain the suitable adjustment of operating conditions. The feeding rate ranged between 40 and 50kg/h, the feed pulp density ranged between 6-10 wt%, and the washing water between 1.65 and 2.75 l/min. Using several adjustments of the operating conditions, C1 and C2 were mixed and treated on several batches by shaking table (Figure 3(3)), and finally three fractions were obtained. The final obtained tabled concentrate C3 weighs 33.87kg and contains 30.44 wt% HM. The final obtained tabled middling M3 weighs 48.8kg and contains 4.66 wt% HM. The final obtained tabled tailings (T3) weighs 77.53 wt%, and contains 1.25 wt% HM Table III. These three fractions represent 21.14, 30.46, and 48.4 wt% of the treated feed respectively. On using the most effective adjustment of operating conditions as 50kg/h

feeding rate, 7.5 wt% feed pulp density, and 2.5 l/min washing water, the obtained tabled tailing (T3a) represents 71 wt% of the treated feed and contains 0.75 wt% of heavy minerals.

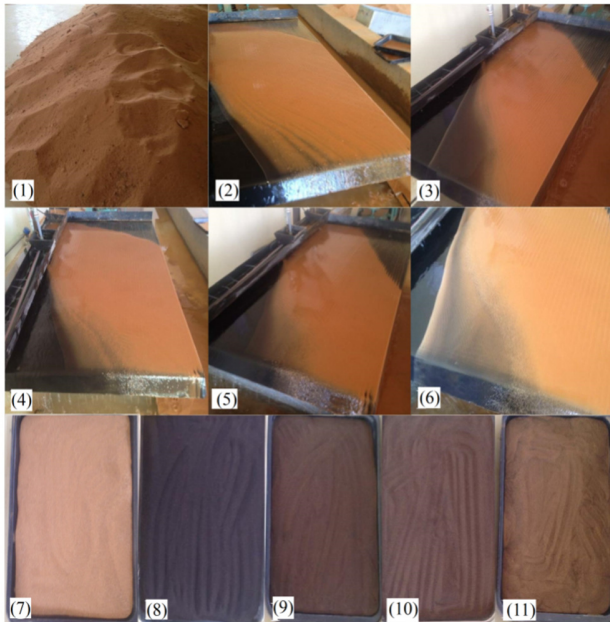


Fig. 3. The various treated fractions using the wet gravity concentration by shaking table and the different obtained magnetic and nonmagnetic fractions: (1) the collected raw sand, (2) the rougher tabling of raw sand, (3) the cleaner tabling of the obtained two tabled concentrates, (4) the scavenger tabling of the obtained tabled middling (M1), (5) the scavenger tabling of the obtained two tabled middlings (M1 and M2), (6) the tabling of the non magnetic fraction containing zircon and rutile, (7) the obtained nonmagnetic fraction at 1.5A, (8) the obtained magnetic fraction at 0.05A, (9) the obtained magnetic fraction at 0.3A, (10) the obtained magnetic fraction at 0.6A, and (11) the obtained magnetic fraction at 1.5A.

TABLE III. OBTAINED TABLED FRACTIONS WITH THEIR SYMBOLS, WEIGHTS, HEAVY BROMOFORM FRACTIONS, AND CORRESPONDING ORIGINAL CONTENTS

Item	Deperated fraction	Heavy content, %	Original heavy content, %
1	Deslimed raw sediments	1.61	1.55
2	Rougher concentrate	8.15	0.84
3	Rougher middling	2.85	0.43
4	Rougher tailings	0.40	0.29
5	Scavenger concentrate	10.00	0.18
6	Scavenger middling	3.43	0.08
7	Scavenger tailings	1.51	0.16
8	Cleaner concentrate	30.44	0.80
9	Cleaner middling	4.66	0.18
10	Cleaner tailings	1.25	0.075
11	Concentrate of M2+M3	15.13	0.102
12	Tailings of M2+M3	2.83	0.154
13	Concentrate of T2+T3	10.24	0.046
14	Tailings of T2+T3	1.18	0.197
15	Non-magnetic fraction of back magnetic separation	6.09	0.089
16	Tabled non-magnetic tailings	0.96	0.021
17	Tabled non-magnetic zircon and rutile concentrate fraction	30.00	0.08
18	Bulk magnetic fraction of back magnetic separation	70.00	0.81

It was noticed that some of the relatively larger composite grains of grain sizes smaller than 2mm and larger than 0.6mm were increased and were collected within the tabled concentrate (C3). These composite grains were most probably composed of calcareous and sand materials. They were noticed with C1 and C2 but with relatively lower contents. Screening using an aperture screen of 0.6mm was carried out for the obtained C3 concentrate. An oversize (+0.6mm) fraction weighing 4.06kg was obtained (Figure 2). However, these composite grains are not too hard and can be effectively diminished in size using one or two stages of attritioning process at the top of the flowsheet of Figure 2. In this case, the process of the non-economic screening stage using a 0.6mm aperture screen can be neglected.

#### c) Scavenger Wet Gravity Concentration

The obtained tabled rougher middling (M1) was treated with the shaking table (Figure 3(4)), and 3 tabled fractions were obtained. The tabled concentrate (C2) weighs 23.41kg and contains 10 wt% HM, the tabled middling (M2) weighs 29.98kg and contains 3.43 wt% HM, and the tabled tailings (T2) weighs 143.93kg and contains 1.51 wt% HM (Table III). These three obtained fractions represent 11.86, 15.19, and 72.94 wt% of the treated rougher middling respectively. The parameters of the shaking table were: 75kg/h feeding rate, 13 wt% feed pulp density, 2.1 l/min and washing water.

#### d) Wet Gravity Concentration of the Obtained Middling and Tailings fractions

Both M2 and M3 middling fractions were mixed and treated by the shaking table (Figure 3(5)) to obtain two fractions: the tabled concentrate (CM2M3) and the tabled tailings (TM2M3). The used shaking table parameters are: 60kg/h feeding rate, 10 wt% feed pulp density, and 1.6 l/min washing water. Also, both T2 and T3 tailings fractions were mixed and treated by the shaking table to obtain two fractions: the tabled concentrate (CT2T3) and the tabled tailings (TT2T3). The used shaking table parameters are: 100kg/h feeding rate, 12 wt% feed pulp density, and 2.2 l/min washing water.

#### e) Magnetic Separation and Fractionation

To obtain most of the magnetic economic minerals, the process of magnetic separation is suggested due to the scarcity of water in the region. More than 25 wt% of the weight of the obtained final concentrates C3, CM2M3 and CT2T3 are magnetic minerals. Most operating conditions for magnetic separators are explained in [16-17] in order to obtain the most magnetic minerals in only one magnetic fraction of a relatively smaller weight and using only one stage of dry magnetic separation. More efficient wet high intensity magnetic separation can be carried out only for such obtained small magnetic fractions, at various successive current values.

The used operating conditions for the first dry magnetic separation and the fractionated dry magnetic separation are: 10kg/h feeding rate, 140rpm magnetic drum speed, 2mm air gap, and 2A current for the first magnetic separation and are 0.05, 0.3, 0.6 and 1.5 for the successive four current values for the second magnetic separation circuit (Figure 2).

f) *Cleaning Wet Gravity Concentration of Zircon and Rutile Minerals Fraction*

A bulk non-magnetic fraction is obtained by mixing the nonmagnetic fraction obtained from the C3 tabled concentrate at 2A with the non-magnetic fraction of the magnetic separation at 2A of the mixed CM2M3 and CT2T3 tabled fractions in addition to the obtained non-magnetic fraction at 1.5A due to the magnetic separation of the obtained bulk magnetic fraction (Figure 2). Finally, the obtained bulk non-magnetic fraction weighs 31.42kg and contains 4.08 wt% HM (Table III). Most magnetite and goethite were separated and contained in the obtained magnetic fractions. The majority of zircon and rutile mineral grains were contained in the obtained non-magnetic fraction at 1.5A. The specific gravity of zircon mineral grains is 4.6 and that of rutile is 4.2, while most of the associated gangue mineral grains have specific gravities ranging between 3.4 and 2.65. Then, a circuit of wet gravity concentration using shaking tables (Figure 3(6)) was carried out for the aforementioned bulk non-magnetic fraction. Two tabled fractions were obtained, the tabled concentrate, weighing 3.37kg and containing 30 wt% HM and the tabled tailings, weighing 28.05kg and containing 0.96 wt% HM

(Table III). The obtained tabled middlings are recycled with the treated feed. The used shaking table parameters are feeding rate of 40kg/hour, feed pulp density of 5 wt%, and washing water of 2.75 l/min. The mineral composition of the heavy bromoform fractions of the different obtained tabled fractions in addition to the deslimed original raw sand sample are given in Table IV. Using the same stages of concentration and separation of the flowsheet of Figure 2, another sample of 3400kg of the investigated sediments was treated and finally 49.73kg were obtained as bulk magnetic fraction. Due to the back magnetic separation at 2A, two non-magnetic fractions were obtained at 2 and 1.5A weighing 152.43kg and 7.52kg respectively. The bulk magnetic fraction (49.73kg) was treated through four successive stages of magnetic separation at four different successive current values: 0.05, 0.3, 0.6, and 1.5A. The non-magnetic fraction of the magnetic separation stage at 0.05A is considered the feed of the second magnetic separation stage at 0.3A. The nonmagnetic fraction of the last separation stage is the feed of the third magnetic separation stage at 0.6A where the obtained nonmagnetic fraction is the feed of the final four magnetic separation stage at 1.5A.

TABLE IV. HEAVY AND ECONOMIC MINERAL CONTENTS OF THE OBTAINED VARIOUS TABLED FRACTIONS WITH THEIR CORRESPONDING CONTENTS OF THE HEAVY BROMOFORM FRACTION (H Br FR) WEIGHT PERCENTAGES

Fractions	Heavy fractions %.	Mineral components of heavy fractions %								
		Carbonates	Pyroxenes	Goethite	Ilmenite	Rutile	Zircon	Monazite	Magnetite	Quartz
T1	0.40	1.41	86.49	12.08	0.00	0.00	0.00	0.00	0.00	0.00
T1a	1.00	3.10	71.00	6.40	0.00	0.00	0.00	0.00	19.5	0.00
T1b	0.67	1.40	91.90	6.70	0.00	0.00	0.00	0.00	0.00	0.00
T2	1.51	1.82	91.30	4.07	0.00	1.74	1.09	0.00	0.00	0.00
T3	1.25	0.78	92.70	3.72	0.00	3.45	0.00	0.00	0.00	0.00
T3a	0.75	1.90	94.2	3.20	0.00	0.00	0.00	0.00	0.00	0.00
T4	0.96	1.38	93.11	4.02	0.00	1.48	0.00	0.00	0.00	0.00
M1	2.85	1.64	86.83	3.24	3.83	1.30	1.53	0.00	1.66	0.00
M2	3.43	0.98	91.52	4.89	0.55	0.98	1.08	0.00	0.00	0.00
M3	4.66	0.41	90.04	5.96	0.46	1.03	1.58	0.51	0.00	0.00
CM2M3	15.13	0.60	78.50	13.10	1.30	2.50	3.30	0.70	0.00	0.00
TM2M3	2.83	0.60	98.40	0.70	0.00	0.00	0.20	0.10	0.00	0.00
CT2T3	10.20	1.40	77.30	11.30	0.00	5.00	4.30	0.80	0.00	0.00
TT2T3	1.20	1.50	94.80	2.30	0.00	1.60	0.00	0.00	0.00	0.00
C1	8.15	0.816	35.651	11.531	13.69	3.10	7.50	3.03	24.68	0.00
C2	10.00	1.688	80.870	1.80	8.62	1.09	2.18	0.00	3.76	0.00
C3 nm	6.09	1.01	13.32	0.00	0.00	23.29	62.38	0.00	0.00	0.00
Deslimed raw sand	1.61	1.150	59.054	9.371	8.46	2.03	4.48	1.64	13.82	0.00
Light Br. Fr. of raw sand		8.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	91.50

Finally, another four successive magnetic fractions were obtained: at 0.05A, weighing 12.67kg, at 0.3A, weighing 7.58kg, at 0.6A, weighing 12.86kg, and at 1.5A, weighing 9.10kg. The obtained non-magnetic fraction at 1.5A weighs 7.52kg. The final obtained non-magnetic fraction at 1.5A was mixed with the non-magnetic fraction at 2A and a bulk non-magnetic fraction of 159.95kg was obtained and was subjected to wet gravity concentration using the available half-size shaking table. The final tabled zircon and rutile fractions weighing 7.67kg and containing 35 wt% zircon and rutile were obtained.

Each obtained magnetic fraction was mixed with the corresponding obtained one of the treated 1290kg sample (see the flowsheet in Figure 2) along with the two obtained zircon and rutile fractions of the two treated samples, weighing 1290

and 3400kg, and the following obtained five concentrate fractions were obtained: The tabled zircon and rutile fraction, weighing 11.04kg (Figure 3(7)), the magnetic fraction at 0.05A, weighing 17.04kg (Figure 3(8)), the magnetic fraction at 0.3A, weighing 9.58kg (Figure 3(9)), the magnetic fraction at 0.6A, weighing 16.89kg (Figure 3(10)), and the magnetic fraction at 1.5A, weighing 11.59kg (Figure 3(11)).

C. *The Mineralogical Investigation*

Most of the detected heavy and economic minerals are concentrated in relatively finer grain sizes. Almost all of them are present in the undersize fraction of a screen with an aperture of 0.5mm. Most previous studies ensured that heavy minerals are highly concentrated in the relatively finer grain size classes [18-19].

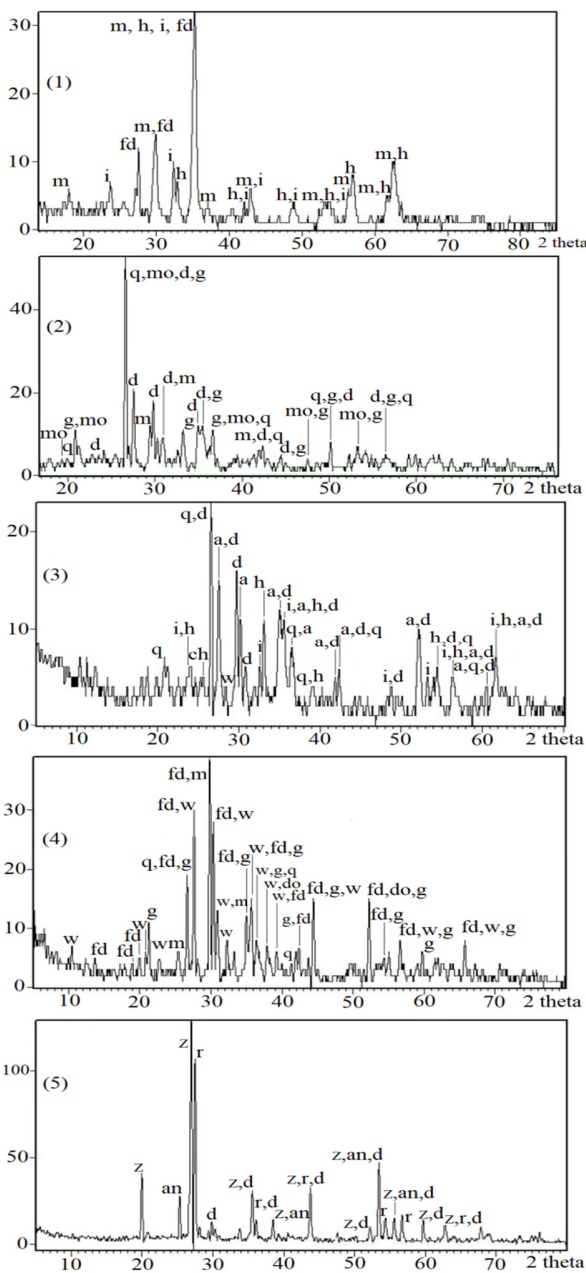


Fig. 4. XRD patterns of the different separated fractions: (1) ferromagnetic fraction separated at 0.05A, (2) magnetic fraction separated at 0.3A, (3) magnetic fraction separated at 0.6A, (4) magnetic fraction separated at 1.5A, (5) heavy bromoform fraction obtained from the separated tabled nonmagnetic fraction at 1.5A. m=magnetite, i=ilmenite, h=hematite, mo=monazite, g=goethite, q=quartz, d=diopside, fd=ferrian diopside, a=augite, do=dolomite, w=winchite, c=calcite, ch=chlorite, z=zircon, r=rutile, and an=anatase.

It was noticed that a considerable portion of quartz grains, present particularly in the finer grain sizes, are stained with reddish to pink materials in addition to the presence of inclusions of opaque inclusions. Therefore, the quartz grains are met in most obtained magnetic fractions, either at 0.05, 0.6, or 1.5A. The heavy silicate minerals are relatively coarser than most economic minerals grains. The grains are subrounded,

rounded to well rounded, elongated more than spherical with highly pitted surfaces. Many of their grains are locked or stained with magnetite fragments or inclusions. They have different color shades of dark green, green, brown, yellowish to opaque. According to the XRD identification, their majority are monoclinic pyroxenes of augite and diopside in addition to minor winchite (monoclinic amphiboles). Most of the magnetite grains are iron black and have a chain structure which is characteristic for the ferromagnetic grains of high magnetic susceptibilities. Most of the grains have relatively finer grain sizes, they are angular to subangular or subrounded and spherical. Many of the grains have cubic octahedron crystals. Several grains are stained or locked with small parts of silicate minerals, most probably ferrian diopside. The identified XRD pattern of a sample of the obtained 0.05A magnetic fraction is given in Figure 4(1). The presence of ilmenite and hematite in subordinate contents is noticed. The essential line of ferrian diopside is also given in the pattern. The identified mineral patterns of magnetite, ilmenite, and hematite are in accordance with the ASTM Cards 86-1355, 89-2811, and 13-0534 respectively. It seems that individual ferriilmenite grains or ilmenite exsolved intergrowth with magnetite are present, in addition to the martitization of some magnetite grains. It was noticed that for most of the obtained magnetic fractions of various different samples of the same studied area, the same mineral can be identified by more than one ASTM cards. For example, magnetite can be identified with the ASTM cards No. 86-1355, 086-1340, 75-1609, or 19-629. This may reflect the diversity of magnetite grains with respect to the source area, grain mineral chemistry, exsolution, inclusions or also the types of associated minerals in the identified sample. The EDX analysis of an area of a sample from the obtained magnetite fraction at 0.05A is shown in Figure 5(1). Both K and Al are related to the presence of minor muscovite in the ferromagnetic fraction.

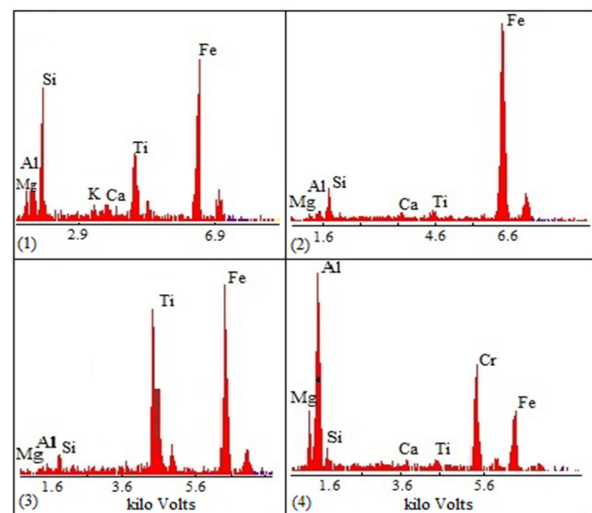


Fig. 5. EDX chemical analyses of the different obtained economic minerals: (1) an area chemical analysis of the ferromagnetic fraction separated at 0.05A, (2) a spot chemical analysis of a hematite grain separated at 0.3A, (3) a spot chemical analysis of an ilmenite grain separated at 0.3A, (4) a spot chemical analysis of a most probably chromspinell grain separated at 0.3A.



The detected ilmenite grains are angular to subangular of grey color with bluish tints. The XRD pattern of a sample of the obtained magnetic fraction at 0.3A is shown in Figure 4(2). The fraction is composed mainly of quartz, diopside, augite, ilmenite, and hematite, in accordance with the ASTM Cards 89-8936, 082-0460, 24-0203, 003-0781, and 013-0534. Minor portions of winchite, chlorite, and kaolinite are also noticed in the pattern. The EDX analyses of a hematite and ilmenite individual grains in the obtained fraction are shown in Figure 5(2)-(3). The EDX analysis of one of the detected grains identified under the binocular microscope as pyroxene, gives the chemical analysis of most probably Cr-spinel (Figure 5(4)).

In the obtained magnetic fraction at 0.6A, monazite and goethite are detected. Most of monazite grains are rounded to well rounded, of yellowish to pale yellowish color and have relatively finer grain sizes. The XRD pattern of the fraction reflects its composition of quartz, diopside, goethite, and monazite (Figure 4(3)), in accordance with the ASTM cards 79-1906, 71-1494, 17-0536, and 11-556. The EDX analysis of two individual grains, one for monazite and one for xenotime are shown in Figure 6(1)-(2). In fact, the second grain was thought to be monazite or magnetic zircon. It is well rounded elongated, colorless with pale yellowish tint color. The chemical analysis of the first monazite grain reflects the composition of rare earth elements, essentially Ce, La, Nd, Pr, Sm, and Gd, phosphate in addition to Ca, Th, and U silicates. Also, Fe, Al, Mg and K are recorded.

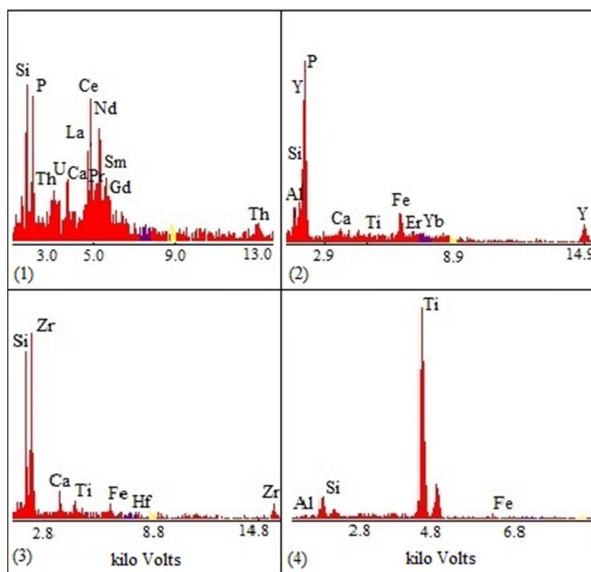


Fig. 6. EDX chemical analyses of the different obtained economic minerals: (1) spot chemical analysis of a monazite grain separated at 0.3A, (2) spot chemical analysis of a xenotime grain separated at 0.3A, (3) spot chemical analysis of a zircon grain separated as nonmagnetic at 1.5A, and (4) spot chemical analysis of a rutile grain separated as non-magnetic at 1.5A.

It is known that Th and U are incorporated by two exchange mechanisms in monazite and xenotime [20-27]: The brabantite exchange:  $(Th, U)^{4+} Ca^{2+} = 2REE^{3+}$  and the huttonite exchange:  $(Th, U)^{4+} Si^{4+} = REE^{3+} P^{5+}$ . It is obvious that the detected monazite is not homogeneous but contains exsolved

intergrown with both huttonite and brabantite. The chemical analysis of xenotime reflects the composition of Y, P and some heavy rare earths: Er and Yb. Due to the presence of these radioactive minerals, the Water Quality Index (WQI) and the Irrigation Water Quality (IWQ) of the groundwater in the area can help us determine the quality and drinkability of this water [28-29]. The XRD pattern of a representative sample of the magnetic fraction obtained at 1.5A gives the mineral composition of ferrian diopside, quartz, goethite, dolomite and winchite (Figure 4(4)). These minerals are in accordance with the ASTM cards 83-0102, 78-2315, 08-0097, 34-0517, and 020-1390. The goethite grains are minor in the fraction, and have brownish, reddish, yellowish to grayish opaque color.

The XRD pattern of the heavy bromoform fraction of the tabled non-magnetic fraction at 1.5A reflects the composition of zircon, rutile, anatase in addition to diopside and calcite (Figure 4(5)), in accordance with the ASTM Cards 81-0588, 72, 1148, 02-0387, 75-1092, and 5-586. The EDX analysis of two individual grains, one for zircon and the one for rutile are shown in Figure 6(3)-(4). The majority of zircon grains are prismatic, elongated, and spherical. The grains are mainly colorless with a considerable number stained with pink material. The majority of rutile grains have black, brown, red to dark-red colors. The grains are mainly elongated subangular to subrounded in shapes. Several grains are very fine acicular prismatic. The detected anatase grains are bluish in color, relatively coarser than rutile.

Virtually, it is the first time such a study is applied to the fraiible sediments of the Northern Border Region for economic mineral identification and their mineability of concentration and separation. The presence of zircon and rutile was ensured in addition to the other iron-bearing minerals. The suggested separation flowsheet of the different recorded economic minerals will be a guide for their industrial exploitation. In fact, there are no previous similar works, neither for economic mineral identification nor for their separation, except that of [5] for economic mineral identification of one of the Wadies extended in the present area where the concluded content of total economic minerals was very low and most of the studied sediment locations were inside the Arar city. Also, not all the recorded minerals in the present study were detected in [5].

## V. CONCLUSIONS

The detected heavy and economic minerals were recorded for the first time in the studied area. Most of the recorded heavy minerals are totally concentrated in relatively fine grain sizes, finer than  $500\mu$ . On the other hand, the majority of the detected economic minerals have grain sizes finer than  $250\mu$ . The calculated original heavy mineral content equals to 1.55 wt%. The majority of heavy minerals are monoclinic pyroxene, mainly augite and diopside, in addition to minor monoclinic amphibole, mainly winchite. The identified economic minerals are magnetite ( $Fe_3O_4$ ), ilmenite ( $FeTiO_3$ ), goethite ( $FeOOH$ ), zircon ( $ZrSiO_4$ ), rutile ( $TiO_2$ ), anatase ( $TiO_2$ ), monazite [ $(Ce, La, Nd)PO_4$ ], and xenotime ( $YPO_4$ ). The detected monazite is not homogeneous, it contains exsolved intergrowths of huttonite and brabantite in addition to several other light rare earth elements. The detected xenotime contains the heavy rare earth elements Er and Yb. Hematite ( $Fe_2O_3$ ) is also recorded

but it may be composite with the martite magnetite or with the ferriilmenite. The calculated original grades of the detected economic minerals are 0.21 wt% magnetite, 0.15 wt% goethite, 0.13 wt% ilmenite, 0.07 wt% zircon, 0.03 wt% rutile, and 0.025 wt% monazite. Anatase is included within rutile content while xenotime is included within monazite content.

Most of these economic minerals can be easily concentrated and separated in acceptable grades and recoveries. The magnetite can be obtained inside an individual magnetic ferromagnetic fraction using the available dry magnetic separator. On using a wet low intensity magnetic separator, the grade of the obtained concentrate can be increased through one or two stages of separation. Most of zircon and rutile mineral content is obtained in an individual non-magnetic fraction. The associated minerals have specific gravities ranging between 3.4 and 2.65. Both these two economic mineral concentrates can be easily upgraded using the wet gravity concentration by spirals and then subjected to a circuit of the high tension electrostatic separation, where finally rutile is obtained as conductor while zircon is obtained as non-conductor.

Most of the contained ilmenite is obtained in a definite magnetic fraction associated with pyroxenes, amphiboles, and quartz. Then, using both of the wet gravity concentration and/or rare earth roll magnetic separation, ilmenite can be obtained in an individual concentrate.

Goethite and monazite are obtained inside a magnetic fraction by a relatively greater magnetic field. They are associated with pyroxenes and quartz. Then, using wet gravity concentration and electrostatic separation, goethite can be obtained as conductor while monazite is obtained as non-conductor.

As a final conclusion, the presence of zircon, monazite, and xenotime in association with the iron-containing minerals in addition to the major quartz mineral grains, which are stained/coated with iron oxides may lead to the absorption of some radioactive elements on the grain surfaces of the associated minerals. If these three radioactive minerals are represented in relatively higher percentages in some locations, care must be taken in using the most upper surficial deposits in building or agriculture.

#### ACKNOWLEDGEMENT

The authors wish to acknowledge the approval and the support of this research study by the grant No. IF\_2020\_4448 from the Deanship of Scientific Research in Northern Border University (N.B.U.), Arar, Kingdom of Saudi Arabia.

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