Identification of Economic Minerals in Sand Deposits from Northern Saudi Arabia's Border Region

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ABSTRACT

To identify and characterize economic minerals in sand deposits in the Northern Border Region of Saudi Arabia, surficial sand deposit samples from selected areas were collected. The samples exhibited friable characteristics and heterogamous grain-size distributions, consisting mostly of pebbles, granules, sand, and fines less than very coarse silt. Heavy liquid separation, magnetic separation, and microscopic examination using a binocular stereo microscope and an Environmental Scanning Electron Microscope (ESEM) were performed. Mineralogical experiments revealed that the studied sand deposits displayed a relatively narrow range of total heavy contents, such as magnetite (0.76%), ilmenite (0.45%), leucoxene (0.039%), rutile (0.232%), and hematite (0.76%). Moreover, some accessory minerals, such as zircon (0.103%) and garnet (0.004%), as well as scarce monazite, were distinguished. Magnetite (0.76%) and ilmenite (0.45%) minerals were predominant. The variation in the heavy mineral content of surficial sand deposit samples along the northern periphery of Saudi Arabia indicates a significant diversity in the region, particularly within the major paleo-wadis of the Arabian Peninsula in the northern Najd and Hijaz areas. This diversity may reflect the economic significance of the northern border region of the Kingdom of Saudi Arabia. Consequently, it could play a crucial role in the construction and development of mineral processing projects.

Keywords-economic minerals; heavy liquid separation; magnetic separation; microscopic examination

I. INTRODUCTION

The Kingdom of Saudi Arabia is characterized by huge sand deposits. These deposits cover about 635,000 km^2, representing nearly 33% of the total area of the Kingdom. The major sand seas, including the Empty Quarter, Great Nafud, Al Dahnaa, and Al Jafurah, collectively account for about 90% of the bulk sand deposits in the Kingdom. These vast aeolian systems represent significant, yet underutilized, natural resources with potential economic importance, particularly in the context of industrial minerals.

Previous studies on sand deposits in Saudi Arabia have concentrated on geomorphological and environmental aspects. Although some studies have examined the mineralogical composition of sand in specific locations, these investigations were generally limited in scope and geographically constrained. Furthermore, comprehensive evaluations of the economic potential of these sand deposits, particularly in the Northern Border Region, remain scarce. While earlier studies have reported mineralization in nearby areas [1-3], an integrated assessment that combines mineralogical, geochemical, and economic analyses of these sandy deposits is still lacking.

The examined area is located in the far North of the Kingdom of Saudi Arabia (Figure 1), consisting of friable sediments, mostly sand, silt, and some carbonates, lying between latitudes 30º 47' and 30º 54' N and longitudes 40º 48' and 40º 55' E. It is located 30 km from Arar City, Northern Border Region, to the left along the highway between Arar and Sakaka, Al Gouf Region, roughly 20 km in length (Figure 2).

Despite the extensive distribution and potential significance of sand deposits, a notable research gap remains in the detailed mineralogical characterization and economic assessment of these deposits. Insufficient attention has been paid to determining the types, concentrations, and spatial distribution of economically valuable minerals within these sands, as well as evaluating their suitability for industrial use. This lack of comprehensive and integrated studies limits the effective utilization and development of these natural resources.

Therefore, the primary aim of this study is to investigate the mineralogical composition and evaluate the economic potential of selected sand deposits in the Northern Border Region of Saudi Arabia. This was achieved through detailed sampling, separation techniques (including heavy mineral analysis), and laboratory investigations to identify and quantify the valuable mineral constituents.

The originality of this study stems from its integrated approach, which combines field investigations, mineralogical characterization, and economic evaluation of sand deposits in a relatively underexplored region. The findings enhance the understanding of the resource potential of sand deposits in Saudi Arabia and provide a scientific foundation and recommendations for further assessing the economic value of the studied deposits and future mining development.

Fig. 1. Location map of Saudi Arabia showing the studied area in the north.

II. SAMPLING AND METHODOLOGY

Numerous surficial sand samples were collected using a definite grid pattern covering the studied area, as shown in Figure 2, in which each line represents nearly ten stations. The distance between every two successive stations was 2 km. Each station was covered by about 10 surficial samples that were taken at intervals of approximately 250 m, while the average depth ranged between 20 and 30 cm. Each sample weighed 25–30 kg. Thus, about 90 samples were extracted. About three samples were selected from each station, totaling 30 samples from the study area. In addition, three samples were collected from different locations along the examined area, where heavy mineral concentrations were observed on the surface of the deposits.

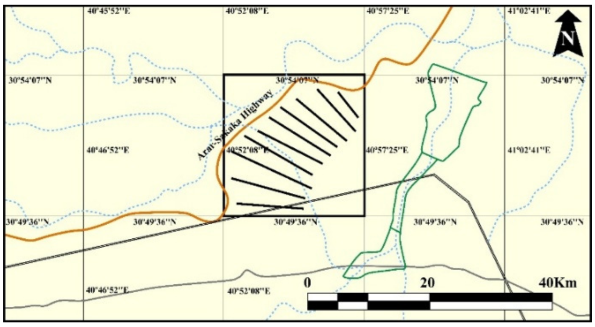

Fig. 2. Map showing the profiles taken.

The sample preparation involved several stages, including:

- An oven was used to eliminate moisture from the samples prior to further processing, ensuring accurate weight measurements and improving the effectiveness of the subsequent preparation steps.
- Screening was carried out using 2 mm and/or 500 µm aperture sieves to remove debris, organic materials, and large sediment fragments, producing a more uniform sample for analysis.
- A Jones riffle splitter was used to divide the bulk sample into smaller portions while maintaining representativeness. This allows the preparation of subsamples of different weights without altering the original composition of the material.
- A mechanical shaker equipped with a series of standard sieves with aperture sizes of 50, 3, 2, 1, 0.5, 0.25, 0.125, 0.063, and 0.045 mm was used to perform sieve analysis. By operating under controlled conditions, the shaker separates the particles into different size fractions, allowing the determination of the particle size distribution of the collected samples.
- The semi-quantitative microanalyses of the grains of the recorded heavy economic minerals were carried out using the Environmental Scanning Electron Microscope (ESEM) model Phillips XL-30. The Energy-Dispersive X-ray (EDX) spectrum illustrates the composition of recorded minerals, and their images were captured by Backscattering Electrons (BSE). All techniques were performed in the Central Labs of Nuclear Materials Authority, NMA, Egypt.

III. RESULTS AND DISCUSSION

This mineralogical study was conducted using several techniques, including heavy liquid separation, bromoform solution, magnetic separation, Frantz Isodynamic magnetic separator, microscopic examination, binocular-stereo microscope, and ESEM.

The sand samples were quartered to obtain a representative sample and then subjected to separation of finer sizes from very coarse silt and organic materials. Next, they underwent heavy liquid separation using a bromoform solution (specific gravity of 2.81 g/cm^3). The solution separated each sample into two fractions: the heavier grains settled at the bottom of the separating flask (heavy bromoform), whereas the lighter grains floated at the top (light bromoform). The percentages of heavy fractions that constitute the total heavy fractions were computed and are shown in Table I and Figure 3(a).

TABLE I. WEIGHT AND PERCENTAGE OF HEAVY AND LIGHT FRACTIONS

S. No.	**Original**	**H. Br.**		**L. Br.**	
		Weight (gr)	**Percentage (%)**	**Weight (gr)**	**Percentage (%)**
A1	29.9494	0.7634	2.6	29.186	97.4
A5	33.1486	0.8674	2.6	32.2812	97.4
A9	65.3377	1.4056	2.2	63.9321	97.8
B3	32.4167	0.6596	2.04	31.7571	97.96
B7	39.1427	1.2373	3.2	37.9054	97.3
B10	30.9904	0.8374	2.7	30.153	97.3
C1	36.8376	0.9393	2.6	35.8983	97.4
C4	33.3734	0.9591	2.9	32.4143	97.1
C8	25.2331	0.5027	1.99	24.7304	98.01
D2	21.4798	0.4003	1.9	21.0795	98.1
D6	33.9502	0.7031	2.1	33.2471	97.9
D10	33.4667	0.4747	1.4	32.992	98.6
E3	31.0631	0.9339	3.0	30.6692	97
E7	29.1252	0.9871	3.4	28.1381	96.5
E10	28.7777	0.6357	2.2	28.142	97.8
F1	18.2004	0.7297	4	17.47034	96
F4	10.3413	0.1769	1.7	10.1644	98.3
F8	37.8405	1.008	2.7	36.8325	97.3
G3	22.7114	0.3028	1.3	22.4086	98.7
G6	39.681	1.143	2.9	38.538	97.1
G9	31.4293	0.8093	2.6	30.62	97.4
H1	21.1333	0.9199	4.4	20.2134	95.6
H4	28.4356	0.7059	2.5	27.7297	97.5
H8	19.5633	1.0427	5.3	18.5206	94.7
I2	32.0928	1.0488	3.3	31.044	96.7
I5	35.4047	0.8771	2.5	34.5276	97.5
I9	34.8914	1.4672	4.2	33.4242	95.8
J1	20.8023	0.8634	4.2	19.9389	95.8
J4	29.4644	0.865	2.9	28.5994	97.1
J8	30.4841	1.1557	3..8	29.3284	96.2
SC2 Mag1	66.6322	1.3369	2.0	65.2953	98
Sand Agr.	43.4215	1.882	4.3	41.5395	95.7
SC Mag1	62.46	4.0448	6.5	58.4152	93.5
Min.	10.3413	0.1769	1.3	10.1644	98.7
Max.	65.3377	1.4672	5.3	65.2953	94.7
Av.	30.56	0.85	2.81	32.034	97.05

Sample Number (S.No.) where letters A, B, C, etc. represent each station, Heavy Bromoform (H. Br.), Light Bromoform (L. Br.)

The magnetite mineral in each heavy fraction was separated using a hand magnet with suitable strength and was weighed. The magnetite percentages were calculated and are shown in Table II and graphically represented in Figure 3(b). A Frantz isodynamic magnetic separator (Model L-1) was used in the laboratory to magnetically separate the magnetite-free portion of each sample at a side slope of 5° and a forward slope of 20° [4]. The results are illustrated in Table III. Each magnetic fraction contains characteristic mineral species. The fractionation was carried out at different magnetic susceptibilities by setting the current at 0.2 A, 0.5 A, 1.0 A, and 1.5 A, corresponding to mass magnetic susceptibilities of 45×10^{-6}, 7.2×10^{-6}, 1.8×10^{-6}, and 0.8×10^{-6}, respectively. All magnetic susceptibility values are expressed in the cgs unit system. The range and average frequency of the magnetic and non-magnetic fractions of the studied samples were calculated and are tabulated in Table IV.

TABLE II. WEIGHT AND PERCENTAGE OF MAGNETITE

S No.	**Original**	**Magnetite**	
		Weight (gr)	**Percentage (%)**
A1	29.9494	0.2228	0.74
A5	33.1486	0.2346	0.71
A9	65.3377	0.3276	0.5
B3	32.4167	0.1844	0.6
B7	39.1427	0.3946	1.0
B10	30.9904	0.1974	0.64
C1	36.8376	0.2546	0.69
C4	33.3734	0.1828	0.55
C8	25.2331	0.1677	0.67
D2	21.4798	0.1306	0.61
D6	33.9502	0.2032	0.60
D10	33.4667	0.1024	0.31
E3	31.0631	0.2617	0.84
E7	29.1252	0.2694	0.93
E10	28.7777	0.1898	0.66
F1	18.2004	0.1232	0.68
F4	10.3413	0.0386	0.37
F8	37.8405	0.3116	0.82
G3	22.7114	0.0769	0.34
G6	39.681	0.3067	0.77
G9	31.4293	0.1967	0.63
H1	21.1333	0.4662	2.21
H4	28.4356	0.1696	0.60-
H8	19.5633	0.4198	2.2
I2	32.0928	0.3918	1.2
I5	35.4047	0.2594	0.73
I9	34.8914	0.4627	1.33
J1	20.8023	0.1464	0.70
J4	29.4644	0.2987	1.0
J8	30.4841	0.379	1.24
SC2 Mag1	66.6322	0.0282	0.04
Sand Agr.	43.4215	0.0263	0.06
SC Mag1	62.46	0.0163	0.03
Min.	10.3413	0.0386	0.3
Max.	65.3377	0.4662	2.21
Av.	30.56	0.25	0.76

The fractions obtained from magnetic fractionation were subjected to microscopic examination. First, a binocular stereo microscope was used for a preliminary investigation to characterize the different minerals composing each magnetic fraction. Furthermore, to obtain the percentage of each mineral in each sample, about 400-1000 mineral grains were counted from each magnetic fractionation. The frequency of each mineral in each magnetic fractionation was estimated, and its percentage was calculated relative to the original sample. The results are listed in Table V and graphically represented in Figures 3-5. Eventually, the semi-quantitative microanalyses of the individual grains of the recorded heavy economic minerals were carried out using the ESEM model Phillips XL-30. The EDX spectrum illustrates the composition of the recorded minerals. All techniques were performed in the Central Labs of Nuclear Materials Authority, NMA, Egypt.

TABLE III. WEIGHT OF THE ISODYNAMIC FRACTION

S. No	**Mag. (0.2 A) 45×10^{-6} cgs**	**Mag. (0.5 A) 7.2×10^{-6} cgs**	**Mag. (1.0 A) 1.8×10^{-6} cgs**	**Mag. (1.5 A) 0.8×10^{-6} cgs**	**Non-mag. (1.5 A) 0.8×10^{-6} cgs**	**Sum.**
A1	0.0698	0.4126	0.0165	0.0063	0.0354	0.5406
A5	0.0898	0.4674	0.0203	0.0137	0.0416	0.6328
A9	0.2209	0.7117	0.0283	0.0131	0.104	1.078

B3	0.064	0.3621	0.0171	0.0052	0.0268	0.4752
B7	0.1075	0.6353	0.0295	0.0105	0.0599	0.8427
B10	0.077	0.3829	0.0284	0.0167	0.135	0.64
C1	0.1006	0.4928	0.0258	0.0058	0.0597	0.6847
C4	0.165	0.4879	0.0188	0.0196	0.085	0.7763
C8	0.0409	0.2535	0.0085	0.0024	0.0297	0.335
D2	0.024	0.1795	0.0167	0.0069	0.0426	0.2697
D6	0.0668	0.3575	0.0204	0.0078	0.0474	0.4999
D10	0.0743	0.2588	0.0078	0.0042	0.0272	0.3723
E3	0.1911	0.4157	0.0144	0.008	0.043	0.6722
E7	0.1459	0.478	0.0247	0.0099	0.0592	0.7177
E10	0.0787	0.2346	0.0155	0.0059	0.1112	0.4459
F1	0.1615	0.3761	0.0167	0.0092	0.043	0.6065
F4	0.0412	0.0835	0.0056	0.008	0.0	0.1383
F8	0.2214	0.4018	0.0161	0.0091	0.048	0.6964
G3	0.0846	0.1224	0.006	0.0033	0.0096	0.2259
G6	0.3499	0.4116	0.0179	0.0088	0.0481	0.8363
G9	0.1479	0.3839	0.016	0.0147	0.0501	0.6126
H1	0.0955	0.3067	0.0149	0.0059	0.0307	0.4537
H4	0.2383	0.2327	0.0131	0.0082	0.044	0.5363
H8	0.0649	0.4391	0.0222	0.0094	0.0873	0.6229
I2	0.0795	0.4933	0.022	0.0088	0.0534	0.657
I5	0.0914	0.4515	0.0222	0.0086	0.044	0.6177
I9	0.3273	0.5614	0.018	0.02	0.0778	1.0045
J1	0.2348	0.2313	0.029	0.027	0.1949	0.717
J4	0.0559	0.4388	0.021	0.006	0.0446	0.5663
J8	0.1174	0.57	0.0237	0.0112	0.0544	0.7767
SC2 Mag1	0.1298	0.9997	0.1126	0.0247	0.0419	1.3087
Sand Agr	1.3369	0.3801	0.0567	0.0128	0.0692	1.8557
SC Mag1	0.5527	3.3989	0.0524	0.0042	0.0203	4.0285

Sample Number (S. No), Magnetic (Mag.), Non-Magnetic (Non-mag.)

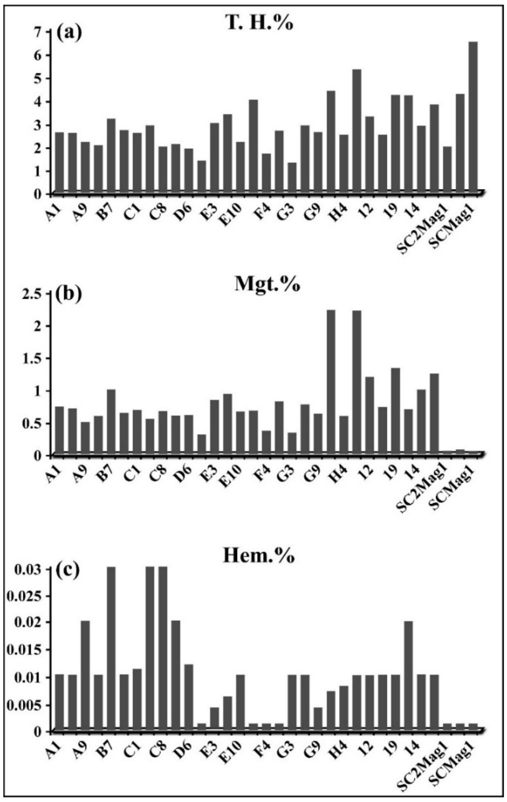

Fig. 3. Histograms of: (a) the distribution of Total Heavy (T.H.) fraction in the studied samples, (b) distribution of the Magnetite (Mgt.) mineral in the studied samples, and (c) distribution of the Hematite (Hem.) mineral in the studied samples.

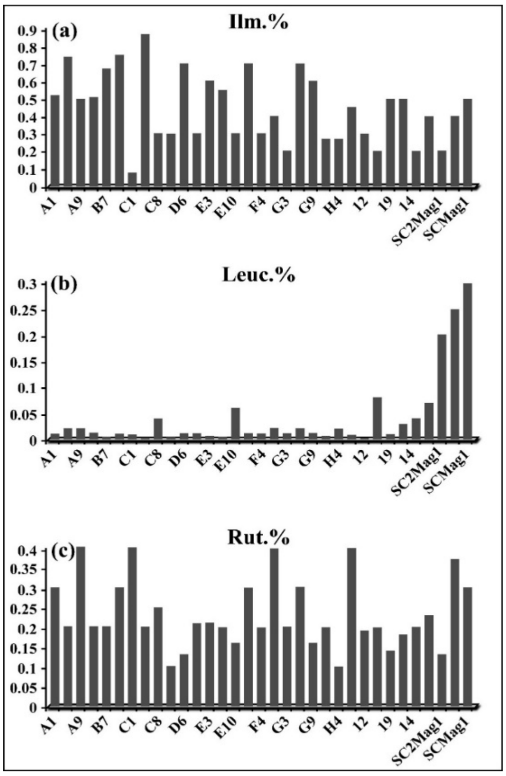

Fig. 4. Histograms of: (a) the distribution of ilmenite in the studied samples, (b) the distribution of leucoxene in the studied samples, and (c) the distribution of rutile in the studied samples.

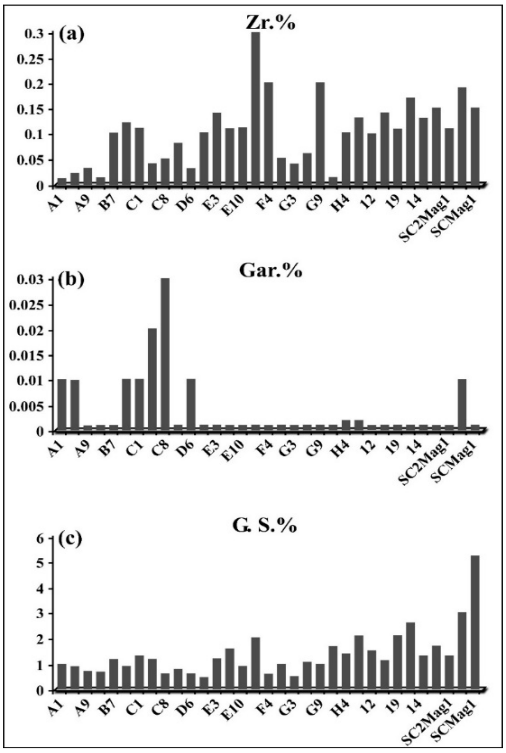

Fig. 5. Histograms of: (a) the distribution of the zircon mineral in the studied samples, (b) the distribution of garnet in the studied samples, and (c) the distribution of green silicate minerals in the studied samples.

The heavy minerals in the sediments are the result of five complex interacting variables, which are the lithology of the source area, differential stability of minerals, durability of the different minerals, hydraulic factor, and post-deposition survival factor [5]. According to [6], the total heavy minerals are concentrated in the medium, fine, and very fine sand size fractions. According to [7, 8], there is a substantial correlation between digenesis and carbonates and sulfates. All mineral species with a specific gravity greater than 2.88 gm/cm^3 are classified as heavy minerals. Sand grains smaller than 0.5 mm were the subject of these studies.

The heavy minerals discovered in the examined area can be divided into two major classes: opaque and non-opaque materials [5]. Magnetite, hematite, ilmenite, leucoxene, chromite, and chromo-spinel are examples of opaque minerals. Rutile, zircon, and garnet are among the second category of non-opaque minerals. Green silicates (epidote, biotite, muscovite, pyroxene, and amphibole families) are compressed by less stable minerals. Additionally, traces of barite, apatite, and monazite were found.

TABLE IV. PERCENTAGES OF THE MAGNETIC FRACTIONS FOR THE STUDIED SAMPLES

S. No.	Mag. % (0.2 A) 45x10^{-6} cgs	Mag. % (0.5 A) 7.2x10^{-6} cgs	Mag. % (1.0 A) 1.8x10^{-6} cgs	Mag. % (1.5 A) 0.8x10^{-6} cgs	Non-mag % (1.5 A) 0.8x10^{-6} cgs
A1	12.912	76.32	3.1	1.17	6.55
A5	14.19	73.86	3.208	2.17	6.57
A9	20.49	66.02	2.625	1.22	9.65
B3	13.47	76.19	3.59	1.09	5.63
B7	12.7566	75.388	3.501	1.245	7.108
B10	12.031	59.828	4.4437	2.609	21.937
C1	14.692	71.973	3.768	0.8470	8.719
C4	21.254	62.849	2.421	2.524	10.949
C8	12.209	75.671	2.537	0.716	8.865
D2	8.898	66.555	0.619	2.558	15.795
D6	13.362	71.514	4.0808	1.5603	9.4818
D10	19.957	69513	2.059	1.128	7.3059
E3	28.129	61.841	2.1422	1.1901	6.396
E7	20.3288	66.6016	3.4415	1.3794	8.2485
E10	17.649	52.612	3.4761	1.3231	24.938
F1	26.628	620115	27535	1.5169	7.0898
F4	29.7903	60.3759	4.04916	5.7845	0
F8	31.7920	576967	2.31188	1.3067	6.8925
G3	37.4501	54.1832	26.560	1.4608	4.2496
G6	41.8390	49.2167	2.1403	1.0522	5.7515
G9	24.1429	62.667	2.6118	2.3996	8.1782
H1	21.4915	67.5997	3.2841	1.3004	6.7665
H4	44.4340	43.3898	2.4426	1.52899	8.2043
H8	10.4190	70.4928	3.5639	1.5090	14.01509
I2	12.100	75.0837	3.3789	1.3394	8.1278
I5	14.7968	73.9373	3.5939	1.3922	7.1231
I9	32.5833	55.8885	1.7919	1.9910	7.7451
J1	32.7475	32.2594	4.0446	3.765	27.1827
J4	9.8710	77.4854	3.70828	1.05950	7.8756
J8	15.1152	73.3874	3.05137	1.4419	7.0039
SC2 Mag1	9.91823	76.3887	8.6039	1.8873	2.324
Sand Agr.	72.04289	20.4828	3.0554	0.6897	3.7290
SC Mag1	13.7197	84.3713	1.3007	0.10425	5.039

Sample Number (S. No), Magnetic (Mag.), Non-Magnetic (Non-mag.)

Magnetite is an important mineral in the mixing triangle of $FeO-Fe_2O_3-TiO_2$. This explains why magnetite frequently occurs in magmatic and metamorphic rocks in conjunction with ulvite (Fe_2TiO_4) and titano-magnetite (solid solution between magnetite and ulvite), as well as ilmenite ($FeTiO_3$) and goethite. Magnetite is mainly utilized in the iron and steel-making industry. It can be used as a dense medium in mineral separation processes.

TABLE V. FREQUENCIES OF THE RECORDED MINERALS IN THE SAND SIZE OF THE STUDIED AREA

S. No.	Mgt. (%)	Hem. (%)	Ilm. (%)	Leuc. (%)	Rut. (%)	Zr. (%)	Gar. (%)	G. S. (%)	T. H. (%)
A1	0.74	0.01	0.52	0.01	0.3	0.01	0.01	1	2.6
A5	0.71	0.01	0.74	0.02	0.2	0.02	0.01	0.89	2.6
A9	0.5	0.02	0.5	0.02	0.4	0.03	0.001	0.73	2.2
B3	0.6	0.01	0.51	0.01	0.2	0.01	0.001	0.7	2.04
B7	1.0	0.03	0.67	0.003	0.2	0.1	0.001	1.2	3.2
B10	0.64	0.01	0.75	0.008	0.3	0.12	0.01	0.9	2.7
C1	0.69	0.011	0.075	0.007	0.4	0.11	0.01	1.3	2.6
C4	0.55	0.03	0.87	0.004	0.2	0.04	0.02	1.19	2.9
C8	0.67	0.03	0.3	0.04	0.25	0.05	0.03	0.62	1.99
D2	0.60	0.02	0.3	0.002	0.1	0.08	0.001	0.8	1.9
D6	0.61	0.012	0.7	0.01	0.13	0.03	0.01	0.63	2.1
D10	0.31	0.001	0.3	0.01	0.21	0.1	0.001	0.47	1.4
E3	0.84	0.004	0.6	0.005	0.21	0.14	0.001	1.2	3
E7	0.93	0.006	0.55	0.003	0.2	0.11	0.001	1.6	3.4
E10	0.66	0.01	0.3	0.06	0.16	0.11	0.001	0.9	2.2
F1	0.68	0.001	0.7	0.01	0.3	0.3	0.001	2	4
F4	0.37	0.001	0.3	0.01	0.2	0.2	0.001	0.6	1.7
F8	0.82	0.001	0.4	0.02	0.4	0.05	0.001	1	2.7
G3	0.34	0.01	0.2	0.01	0.2	0.04	0.001	0.5	1.3
G6	0.77	0.01	0.7	0.02	0.3	0.06	0.001	1.04	2.9
G9	0.63	0.004	0.6	0.01	0.16	0.2	0.001	1	2.6
H1	2.21	0.007	0.27	0.005	0.2	0.01	0.001	1.7	4.4
H4	0.60-	0.008	0.27	0.02	0.1	0.1	0.002	1.4	2.5
H8	2.2	0.01	0.45	0.008	0.4	0.13	0.002	2.1	5.3
I2	1.2	0.01	0.3	0.001	0.19	0.1	0.001	1.5	3.3
I5	0.73	0.01	0.2	0.08	0.2	0.14	0.001	1.14	2.5
I9	1.33	0.01	0.5	0.01	0.14	0.11	0.001	2.1	4.2
J1	0.70	0.02	0.5	0.03	0.18	0.17	0.001	2.6	4.2
J4	1.0	0.01	0.2	0.04	0.2	0.13	0.001	1.32	2.9
J8	1.24	0.01	0.4	0.07	0.23	0.15	0.001	1.7	3.8
SC2Mag1	0.04	0.001	0.2	0.2	0.13	0.11	0.001	1.3	2
Sand Agr	0.06	0.001	0.4	0.25	0.37	0.19	0.01	3	4.3
SC Mag1	0.03	0.001	0.5	0.3	0.3	0.15	0.001	5.2	6.5
Min.	0.03	0.31	0.1	0.001	0.1	0.01	0.001	0.47	1.3
Max.	2.21	2.21	0.87	0.3	0.4	0.3	0.03	5.2	6.5
Av.	0.76	0.76	0.45	0.039	0.232	0.103	0.004	1.374	2.81

Sample number (S. No.), Magnetite (Mgt.), Ilmenite (Ilm.), Hematite (Hem.), Leucoxene (Leuc), Rutile (Rut.), Zircon (Zr.), Garnet (Gar.), Green Silicates (G.S.), Minimum (Min.), Maximum (Max.), Average (Av.)

A. Opaque Minerals

1) Magnetite ($Fe^{2+}Fe_2^{3+}O_4$)

Magnetite typically exhibits a metallic to dull sheen and varies in color from black to a deep reddish-brown tint. The brownish tint can be attributed to its alteration and/or oxidation process. Additionally, there is a high probability of the presence of exsolved phases such as ilmenite and/or hematite. Different types of magnetite–ilmenite intergrowths and their origins have been studied [9-16]. The magnetite habit ranges from massive, granular, and angular to sub-angular. The octahedron crystals of magnetite are less frequent and occur as isolated grains. Magnetite was recorded in all studied sediments, and its content ranged from 0.3 % to 2.21%, with an average of about 0.76%, as displayed in Figure 6(a). The magnetite lattice may contain several elements, such as Mg, Mn, Zn, Ni, Cr, Ti, Al, and V, as pitted magnetite (Figure 6(b)). Also, titano-magnetite was recorded in the present study and contained up to 10% TiO_2 (Figure 6(c)). These results are consistent with those reported in [17].

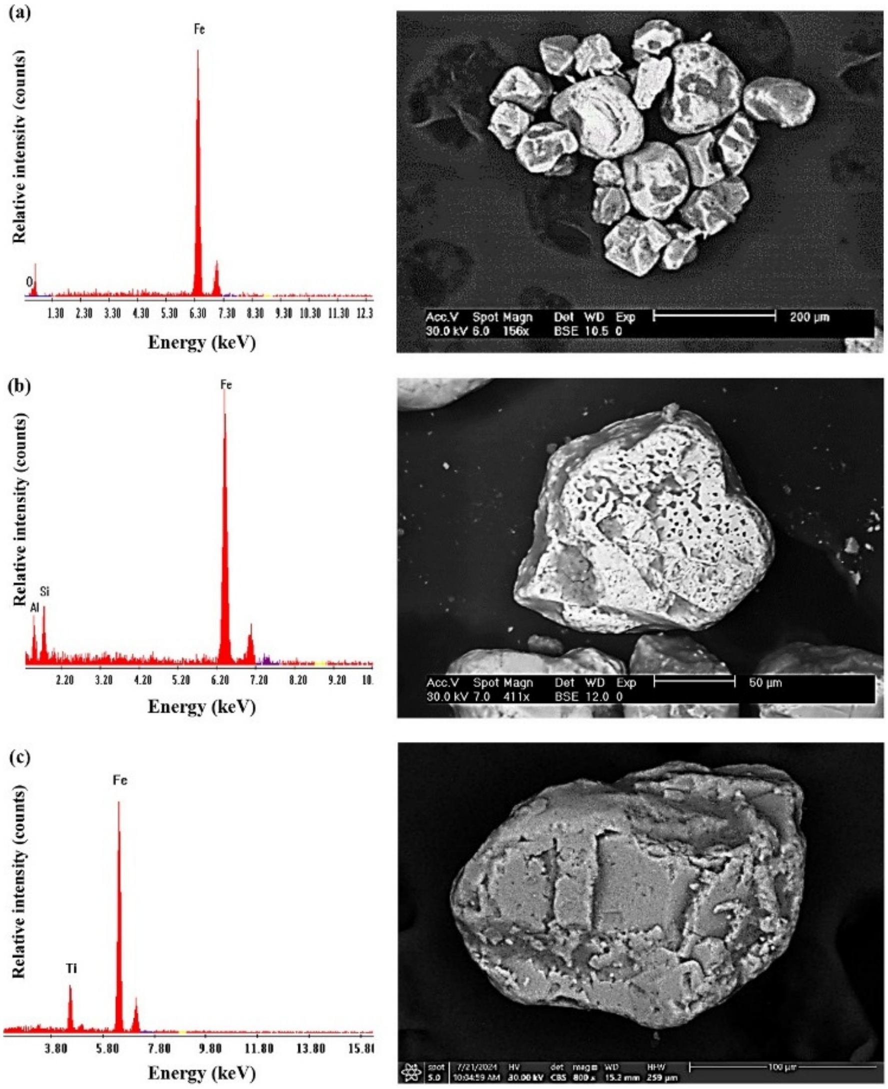

Fig. 6. EDX spectra and BSE images showing: (a) magnetite mineral, (b) highly pitted magnetite, and (c) titano magnetite.

2) *Ilmenite ($FeTiO_3$)*

Ilmenite exhibits an iron-black color with a metallic luster. It occurs as irregular, angular to sub-angular with sharp or smooth edges, oval with smooth and pitted surfaces, well-rounded to sub-rounded, micaceous, and angular with strong striation. Ilmenite is more abundant in finer sand than in medium sand. Ilmenite is a ferromagnetic mineral, so it is mainly separated at magnetic fields generated at 0.2 A and 0.5 A using the isodynamic magnetic separator. Furthermore, it was recorded in all studied sediments, and its content ranged from 0.1% to 0.87%, with an average of approximately 0.45%. Semi-quantitative microanalyses of the concerned ilmenite grains showed a relative percentage of Ti ranging from 48% to 55% (Figure 7(a)), which agrees with the results of [18], in which the TiO_2 content in ilmenite ranged from 45% to 65%. In [13], it was pointed out that approximately 35.48% of the selected ilmenite particles from Baltimore sand dune sediments were derived from a metamorphic source, while 64.52% of these particles were derived from both igneous and metamorphic sources.

Ilmenite is considered the most important ore for titanium extraction; consequently, it is used as a raw material for pigment production as well as in military aircraft and missiles. Now it is extensively used in the paint industry as well as in the rubber, artificial fibers, glass, plastic, paper, textile, and ceramic industries [19-22].

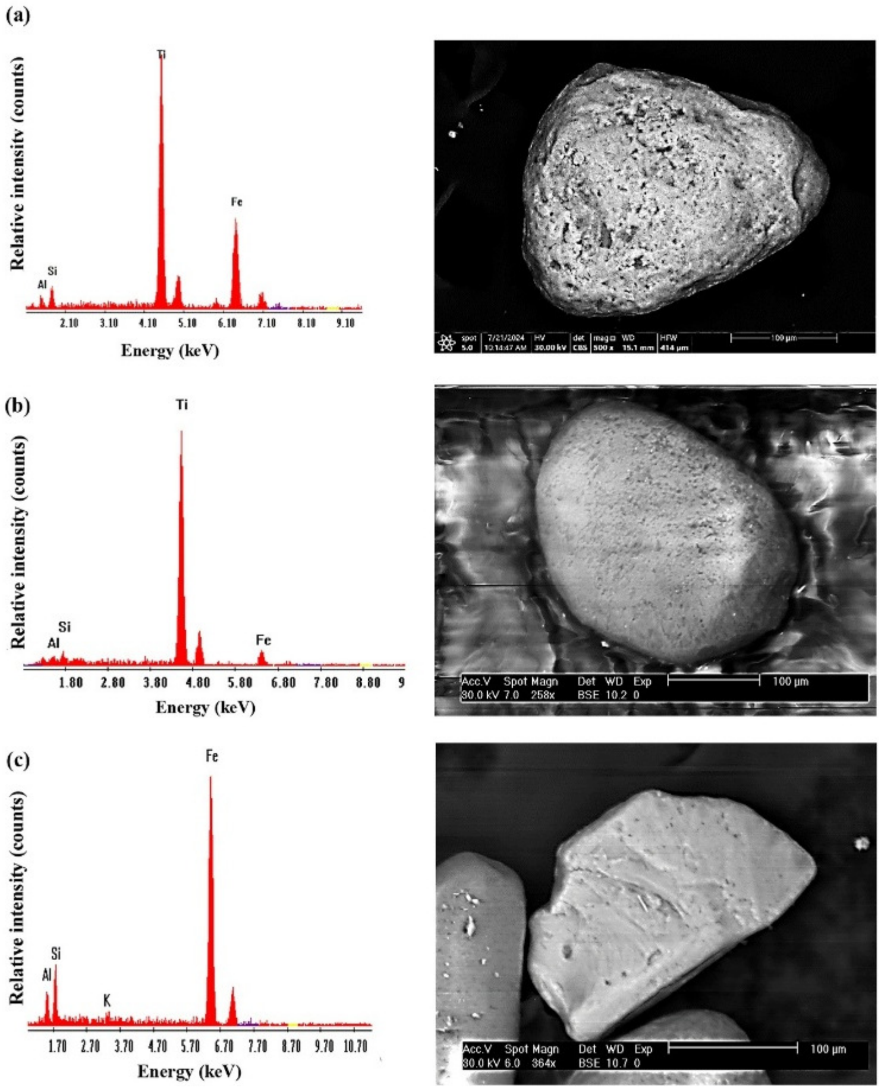

Fig. 7. EDX spectra and BSE images of: (a) ilmenite mineral, (b) highly leucoxene, and (c) hematite.

Also, ilmenite is mainly employed for the manufacture of titanium dioxide white pigment. Titanium dioxide is used as an opacifier in porcelain enamels on steel sheets for refrigerators and sanitary ware. Ceramic titanates are utilized in the electronics industry.

3) *Leucoxene (Mixture of Fe-Ti Oxides)*

Although it is not a mineral, leucoxene is an intermediate state that occurs when ilmenite is altered to create secondary rutile [6, 21, 23]. It appears as amorphous material.

Leucoxene was separated at 1.0 A using the Frantz isodynamic separator. EDX microanalyses revealed that leucoxene contained about 72% TiO_2. These results are in agreement with those of [18], in which the TiO_2 content in leucoxene ranged from 68% to 92%. Leucoxene was recorded in all studied sediments as a common accessory mineral, and its content ranges from 0.001% to 0.3%, with an average of about 0.039% (Figure 7(b)). Its shape ranges from irregular, rounded, subrounded, platy, and prismatic with smooth or pitted surface.

The inherent color of leucoxene can depend on the degree of alteration and TiO_2 content, and the leucoxination process not only affects the overall grade, but also changes the density of mineral grains [24] and their magnetic susceptibility [25]. According to the degree of alteration, the color of leucoxene can change from black, brown, and yellow to white under a binocular stereomicroscope.

The alteration process of ilmenite grains commonly occurs from the outside to the inside through exsolution lamellae, twin planes, cracks, and other zones of weakness. Ilmenite occasionally occurs as relics on the surface of leucoxene, indicating alteration processes. Both SiO_2 and Al_2O_3 impurity levels in the grains increase with increasing leucoxidation process [26].

4) *Hematite (Fe_2O_3)*

Hematite occurs as reddish black to red color and is separated at a magnetic fraction of 0.5 A. Hematite was recorded in all studied sediments, and its content ranged from

0.001% to 0.03%, with an average of about 0.013% (Figure 7(c)). The iron ore, hematite, is typically the result of magnetite alteration processes and the alteration products of numerous Fe-bearing minerals, particularly pyrite and so-called hematite after pyrite (goethite) or pseudomorphic pyrite. Hematite's non-crystalline forms are thought to be changes of the mineral limonite.

B. Non-Opaque Minerals

1) Zircon ($ZrSiO_4$)

Most zircon grains have a euhedral external morphology. Zircon is commonly found as colorless short to long prismatic with bipyramid termination, colorless sub-rounded to rounded, white prismatic with smooth curved edges, and white sub-rounded to rounded. In the present study, zircon was recorded in all concerned sediments as a common accessory mineral, and its content ranged from 0.01% to 0.3%, with an average of about 0.103% (Figure 8). Also, it was concentrated in both magnetic and non-magnetic fractions at 1.5 A. Zircon, separated in the nonmagnetic field 1.5 A, has a long, prismatic, water-clear color with vitreous luster.

According to [27-31], the water-clear zircon grains found in all kinds of rocks are primarily nonmagnetic. The density of tiny inclusions and the intensity of iron oxide staining may be responsible for the difference in zircon's hue. According to [14, 32], certain inclusions may be the result of iron ions that entered from the original melt through the zircon lattice during magmatic crystallization or from an external source. These inclusions are thought to be weak spots that hasten grain breakdown [33].

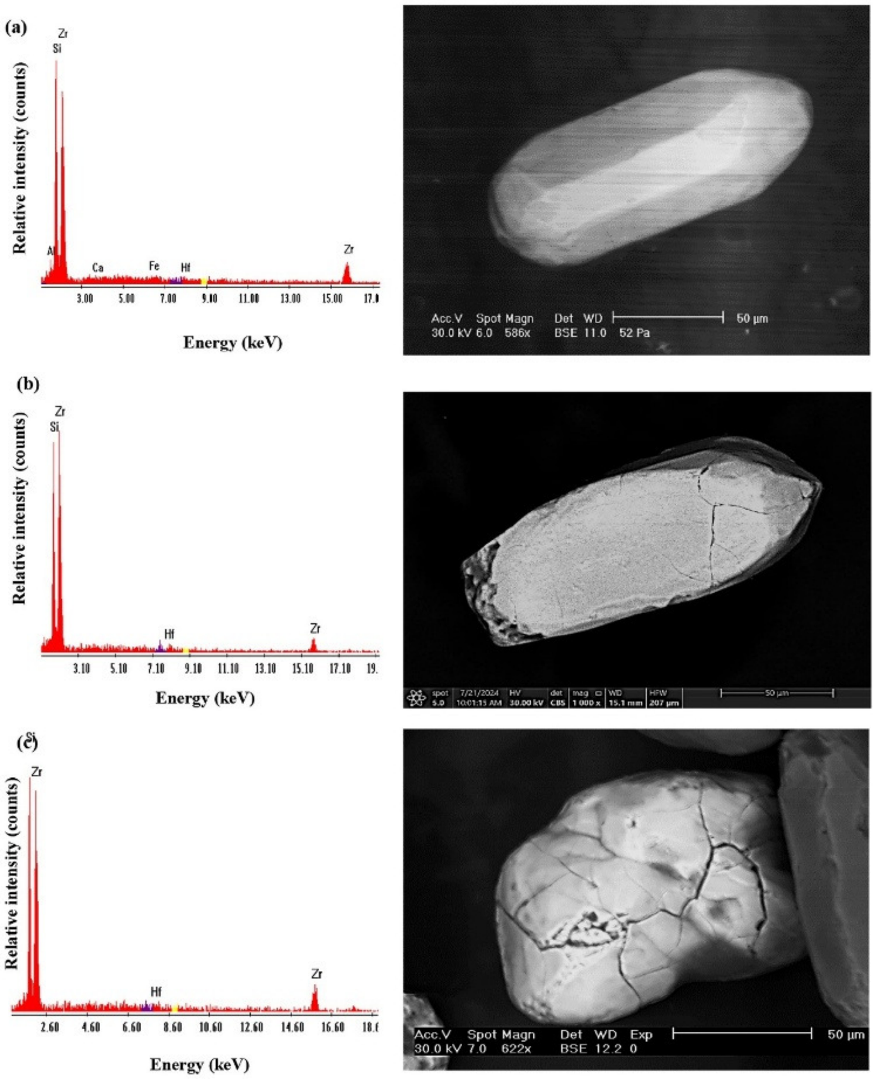

Fig. 8. EDX spectra and BSE images showing zircon mineral exhibiting different habits.

Zircon sand is important in the glass industry, where it is used in making refractory bricks for furnace lining. In addition, zircon is used in the ceramics industry as glazes [34] and is considered the main source of zirconium. Zirconium offers excellent corrosion resistance and, consequently, is widely employed in chemical process equipment, reactor vessels, and aerospace engineering. 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 [20].

2) Garnet

The physical and chemical characteristics of garnet group minerals are closely related. Some metamorphic rocks are characterized by garnet-group minerals, whereas high-pressure igneous rocks have other types. This is the first report of this observation in the examined samples. The studied garnet was found to be angular, colorless, rose, red, subrounded, and well-rounded. Other garnet grains show different degrees of inclusions, which change their color from colorless to black. The studied garnet was separated at magnetic field strengths of 0.2 A and 0.5 using the Frantz isodynamic separator. It ranged from 0.001% to 0.03%, with an average of about 0.004%. Garnet may exist either alone or in a solid solution series, depending on the crystallo-chemical composition of the mixture. Different garnet grain species were recorded and are presented in Figure 9. Almandine ($Fe_3Al_2Si_3O_{12}$), pyrope ($Mg_3Al_2Si_3O_{12}$), spessartine ($Mn_3Al_2Si_3O_{12}$), and andradite ($Ca_3Fe_2Si_3O_{12}$) were the main minerals. The major solid solutions of the studied garnets were almandine-pyrope and almandine-spessartine. Generally, garnet is used as an abrasive. Grape garnet, calderite garnet, rhodolite garnet, and kimzeyite garnet were first recorded as less common garnet varieties in West Rosetta, Egypt [35].

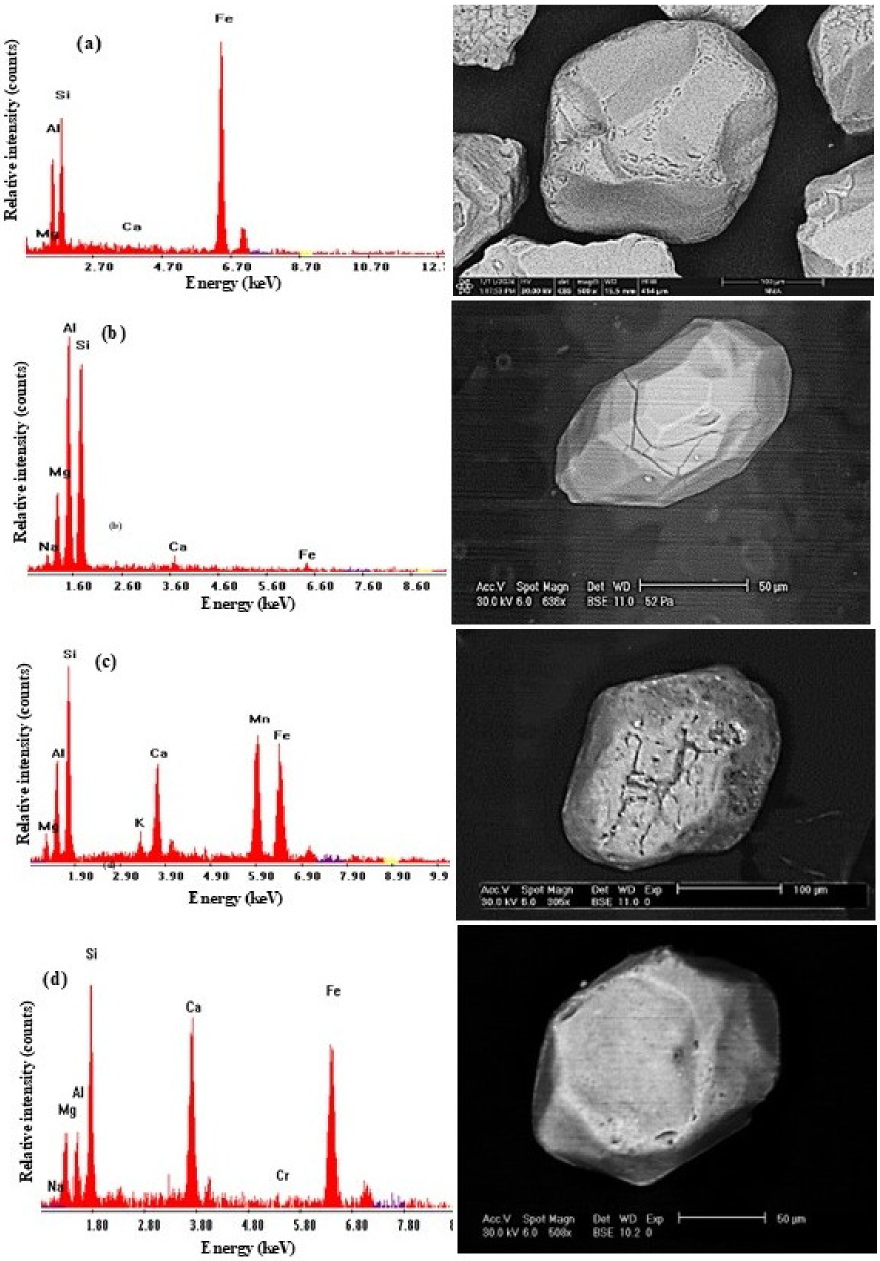

Fig. 9. EDX spectra and BSE images showing garnet varieties: (a) almandine garnet, (b) pyrope garnet, (c) spessartine garnet, and (d) andradite garnet.

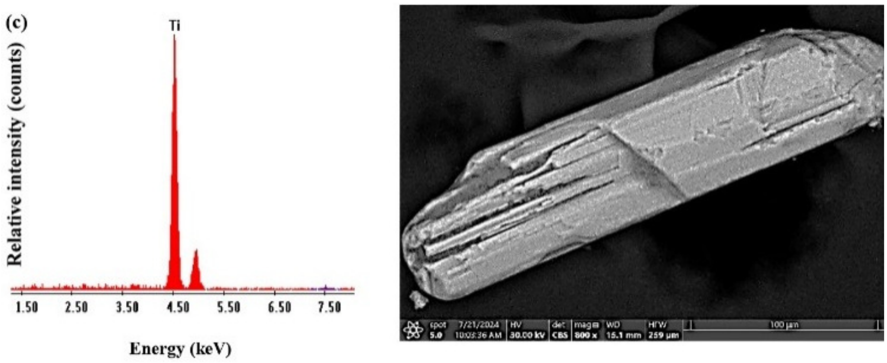

Fig. 10. EDX spectrum and BSE image showing rutile mineral.

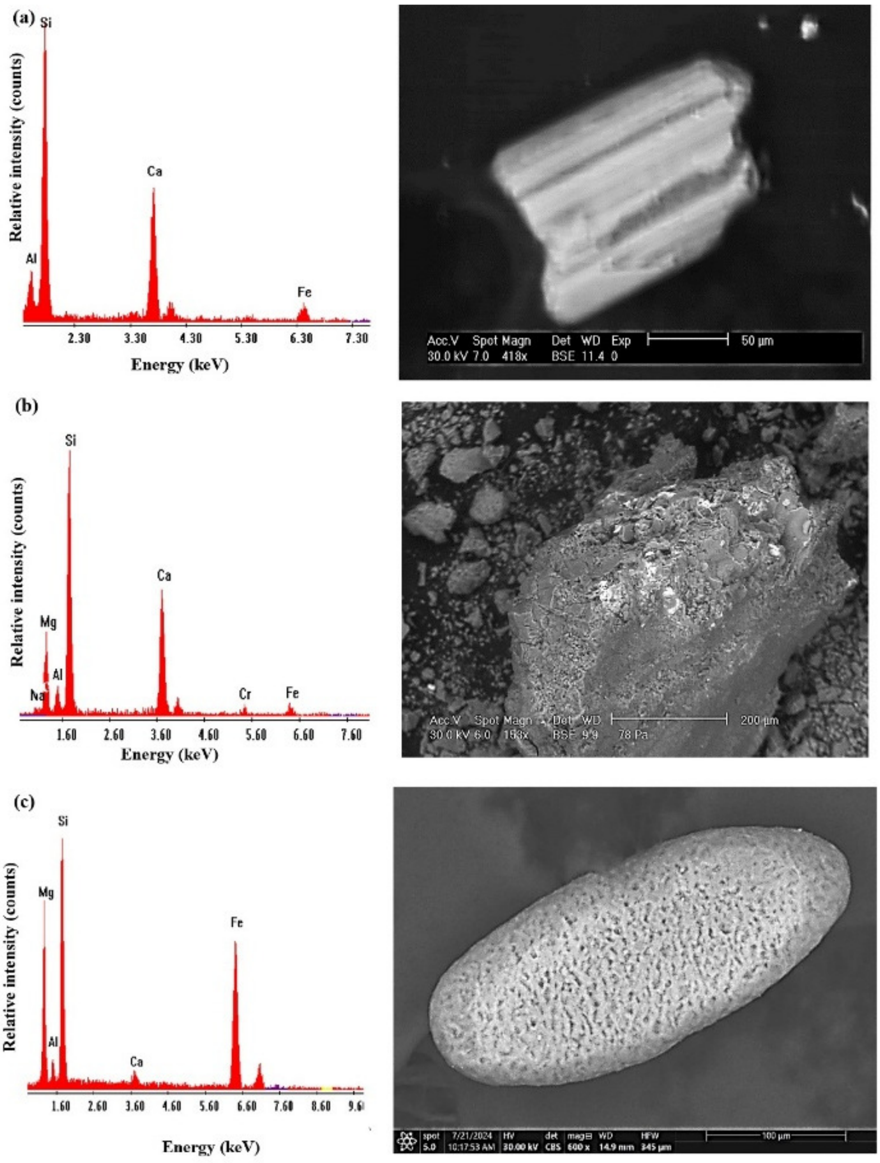

Fig. 11. EDX spectra and BSE images of green silicates showing: (a) epidote, (b) olivine (Monticellite) ($CaMgSiO_4$), and (c) ferro-magnesian silicate: pyroxene.

3) Rutile (TiO$_2$)

Rutile is one of the ultra-stable minerals found in sedimentary rocks. It is used with zircon and tourmaline minerals as an indicator of the maturity of the sediments [13]. It is regarded as an important titanium ore. Rutile can be spherical, long prismatic, short prismatic, or euhedral and anhedral. Less frequently found are the chevron (elbow) rutile type and prismatic grains. Rutile crystallized as a ditetragonal dipyramidal in a tetragonal system. The color of rutile can range from red to blood red to opaque. The Frantz isodynamic separator was used to separate the majority of the rutile grains at a magnetic field intensity of 1.5 A, whereas the remaining rutile was detected in a nonmagnetic 1.5 A fraction. While yellowish and reddish (translucent) rutile is more common in the nonmagnetic portion, the opaque form is more common in the highly magnetic portion. With an average of roughly 0.232%, the measured rutile mineral content varied from 0.1% to 0.4% (Figure 10). Authors in [19] studied the physical properties of zircon and rutile in Rashid beach sand and concluded that Egyptian beach rutile may have been originally derived from a different provenance. Rutile is mainly used in the manufacture of arc-welding electrodes, to produce titanium dioxide electrodes, and as coating materials in tile, in shipbuilding, and other structural steel for which there is a growing demand [36].

4) Less Stable Minerals (Green Silicates)

The term "silicate minerals" refers to minerals composed of silicate groups that are found in rocks. The majority of minerals that form rocks are classified as silicates. Green silicates are the least stable minerals of this group. The studied green silicates were mainly of epidote [$Ca_2(Al_2Fe^{3+})$ (Si_2O_7) (SiO_4) O $(OH)_2$] (Figure 11(a)), olivine (monticellite, $CaMgSiO_4$) (Figure 11(b)), and pyroxene of ferro-magnesian silicate (Figure 11(c)). They were separated during heavy liquid separation in the heavy bromoform. They mainly concentrated on the first magnetic fraction, 0.2 A, and the rest were found in 0.5 A using the Frantz isodynamic separator. The content ranged from 0.47% to 5.2%, with an average of about 1.37%.

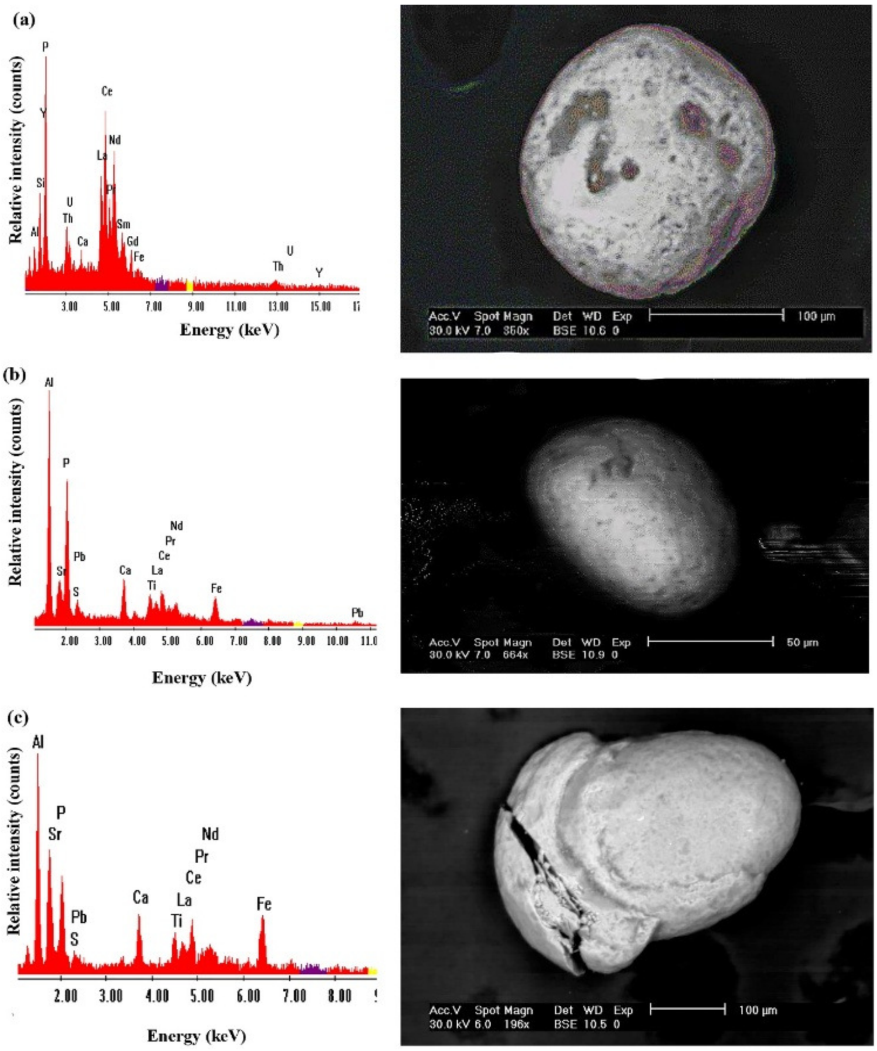

Fig. 12. EDX spectra and BSE images showing: (a) highly radioactive monazite mineral, (b) monazite-free radioactive elements, and (c) monazite with celestite ($SrSO_4$).

C. Trace Minerals

1) Monazite (LREE PO_4)

Generally, monazite is considered a potential source of Light Rare Earth Elements (LREE). It exhibits highly variable compositions. Its color ranges from colorless to lemon yellow, light red, and deep red. In addition, its shapes vary from rounded to discoidal and oval. It occurs as an accessory mineral in fine and very fine sand size fractions in the studied samples. It was separated at a magnetic field strength of 0.5 A. In the present study, it was characterized but scarcely recorded (Figure 12). Monazite is important because of its LREEs, thorium, and uranium content. It is considered the world's primary source of rare earth elements. It contains up to 70% rare earth oxides. It has strategic importance due to its thorium content. Because of its radioactive nature, monazite is useful for radiometric dating of geological events, such as crystallization, heating, or deformation of the rocks containing monazite.

2) Apatite $Ca_5(PO_4)_3F$

Apatite is a rare mineral that is created and utilized by biological microenvironmental systems. It is the primary source of phosphorus required by plants and is the most prevalent phosphate mineral. Most animals, including humans, have the same substances in their bones and teeth. It was noted to have an uneven, wedge-shaped, brown tint in all samples under study (Figure 13). The Frantz isodynamic separator was used to separate it at a magnetic field strength of 1.5 A.

3) Chromite $(Mg, Fe)(Cr, Al)_2O_4$

Chromite was recorded in the study area for the first time. It is sometimes slightly magnetic. Therefore, it is associated with the ilmenite concentrate and is represented by irregular, spherical, and rarely euhedral crystals. It was separated at a magnetic field of 0.5 A (Figures 14(a-c)). It is mainly used to harden steel, manufacture stainless steel, and form alloys. In addition, it is used to give glass an emerald-green color.

4) Barite ($BaSO_4$) and Celestite ($SrSO_4$)

Barite was recorded in the studied area for the first time (Figure 15). Barite is white or colorless, and it is considered the main source of the barium element. Generally, barite and celestite may coexist in a solid solution state. It was separated at magnetic 1.5 A using the isodynamic separator. Barite is commonly used in the production of paints, rubber, and in the medical industry as X-ray shielding. On the other hand, celestite is used in flares and fireworks, ceramic magnets, and even toothpaste for sensitive teeth.

IV. SUMMARY AND CONCLUSIONS

Due to the importance of economic minerals in different industrial, commercial, and strategic applications, it is necessary to focus on their contents and types in the sand deposits in the Northern Borders Region of the Kingdom of Saudi Arabia, with special emphasis on the paragenesis of the essential varieties.

Generally, the surficial sand deposit samples of the selected areas along the northern periphery of Saudi Arabia exhibited friable characteristics and heterogamous grain size distribution, consisting mostly of pebbles, granules, and sand, as well as fine sizes less than the very coarse silt. Nevertheless, the sandy size fraction was relatively dominant and exceeded the other sizes. In addition, it strongly displays different crystal habits. The euhedral particles are less common. Otherwise, the subrounded ones are more frequent and may be closely related to their contribution from other sources.

The mineralogical studies revealed that the studied sand deposits displayed a relatively narrow range of total heavy contents varying from 1.3% to 5.3%, with an average of about 2.8%, possibly due to the shallower depth at which the investigated samples were collected. Generally, the surficial samples do not represent the sedimentary basins. Nevertheless, the high total heavy fraction content was more frequent in darker samples. Particular attention has to be given to digging wells at great depth, which can cause a potential sink of the heavy economic minerals.

The relatively high concentration of heavy minerals is presumably due to a complex series of factors. Among these factors, the interactions between the activity of wind action, extensive weathering, groundwater and surface waters, fluctuation of hydraulics of the stream flow, intensity and distance of transportation from the source, and topographical suitability of the sites for deposition are important.

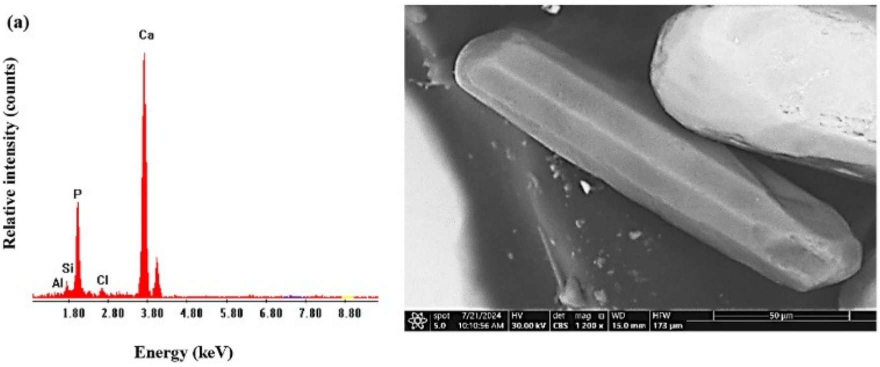

Fig. 13. EDX spectrum and BSE image showing the apatite mineral.

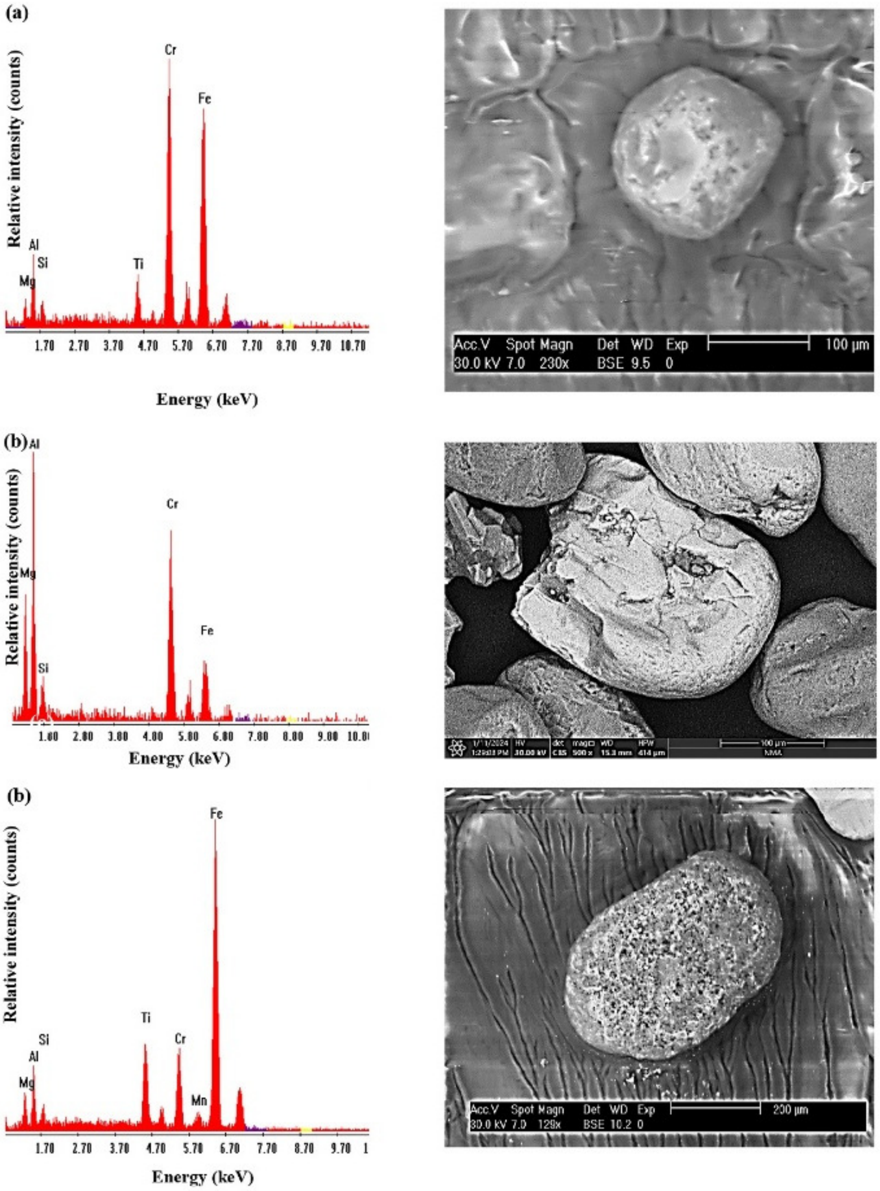

Fig. 14. EDX spectra and BSE images showing: (a) the chromite mineral, (b) chromo-spinel, and (c) Fe-rich chromite.

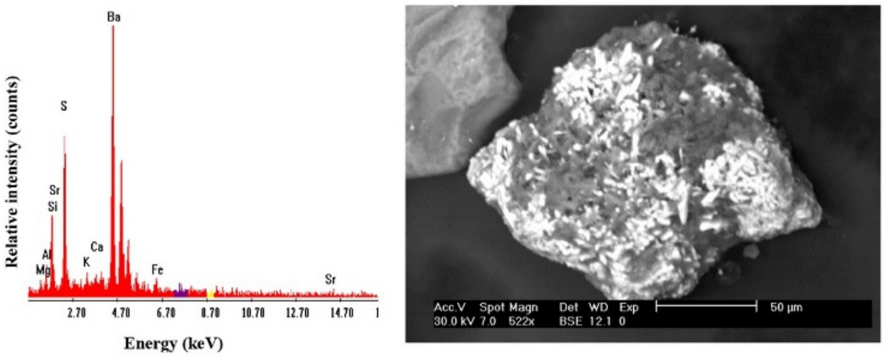

Fig. 15. EDX spectrum and BSE image of the barite mineral.

Microscopy examinations and Energy-Dispersive X-ray (EDX) microanalyses have been successfully applied and proved excellent tools to characterize heavy minerals of economic importance. The existence of intimate coherence of some heavy economic minerals comprising the iron-titanium mineral series, such as magnetite, titano-magnetite, ilmenite, leucoxene, rutile, and hematite, was revealed. Moreover, some accessory minerals, such as zircon and garnet, mainly pyrope, almandine, and spessartine species, have been visually distinguished. The identified garnet minerals may exist either alone or in a solid solution series, depending on the crystallo-chemical composition of the mixture.

On the other hand, monazite mineral as a potential source for the LREE is relatively characterized but scarcely recorded. Furthermore, some particles of apatite, chromite, barite, celestite, epidote, and chromo-spinel have occasionally been recognized. Essentially, ilmenite and zircon minerals are mostly predominant among the recorded economic minerals.

The magnetite minerals varied from 0.3% to 2.21%, with an average of about 0.76%. Ilmenite ranged from 0.1% to 0.87%, with an average of approximately 0.45%. Leucoxene had an average value of about 0.04%. The rutile content varied from 0.1% to 0.4%, with an average of about 0.2%. The zircon content varied from 0.01% to 0.3%, with an average of about 0.1%. The garnet content varied from 0.001% to 0.03%, with an average of about 0.004%. The green silicates varied from 0.47% to 5.2%, with an average of about 1.37%. The examined minerals were apparently free from inclusion. These minerals were mostly enriched in both the medium and fine sand size fractions.

These results are consistent with the findings of [2], in which it was explained that Wadi Arar is one of several main wadies in the Northern Border Region of the Kingdom of Saudi Arabia. The mineralogical investigation of surficial sediments of Wadi Arar reflects the occurrence of some important economic minerals of iron and titanium. According to [37], the variation in heavy mineral distribution in the stream sediments of Wadi Nugrus is controlled by the nature and duration of weathering processes, as well as by the length and power of the transporting agents.

Accordingly, the variation in the heavy mineral content of the surficial sand deposit samples along the northern periphery of the Kingdom of Saudi Arabia strongly suggests diversity in the locality and reveals their derivation from different rock sources. Meanwhile, numerous assumptions have been proposed for deciphering the formation of such sand deposits. The major paleo-wadis in the Arabian Peninsula of the northern Najd and Hijaz areas near the western edge of the Arabian Shield are the possible sources of silicic igneous rocks [38]. In conclusion, the obtained economic minerals are conceivably related to common sources in hinterland areas and could be considered a prominent mineralogical signature of the study sand deposits.

The presence of the concerned heavy economic minerals, as well as the accessory minerals in the studied areas, may play a crucial role in the construction and development of mineral processing projects. Therefore, it may reflect the economic importance of the Northern Region of the Kingdom of Saudi Arabia, hence enhancing urban development in the region.

V. RECOMMENDATIONS

To further assess the economic value of the studied deposits, additional exploration activities are proposed, with a particular focus on drilling deeper wells to examine the continuity and grade of economic minerals at greater depths. Deep drilling can generate more reliable geological information, enhance the accuracy of resource estimation, and potentially reveal new minerals that are not visible near the surface.

Furthermore, establishing partnerships with industrial entities, such as mining companies, drilling service providers, and mineral processing plants, is proposed. These collaborations can offer modern drilling technologies, specialized technical knowledge, and financial resources required for expanded exploration and pilot-scale studies. Such partnerships would help accelerate the evaluation process and support the potential future development of deposits for industrial use.

DECLARATION OF COMPETING INTERESTS

Not applicable to this work.

ACKNOWLEDGMENT

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DATA AVAILABILITY

Not applicable to this work.

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