ISSN : 0974 - 7451 Volume 8 Issue 5

Environmental Science
An Indian Journal

Current Research Paper

ESAIJ, 8(5), 2013 [167-178]

# Application of magnetic susceptibility measurements to study and map heavy mineral spatial distribution patterns in a sample area in Egypt

**Mohamed A.El-Sadek*, Sayed A.Elkhateeb**
**Nuclear Materials Authority, P.O. Box 530 Maadi, Cairo, (EGYPT)**
**E-mail : elsadek_eg@yahoo.com**

## ABSTRACT

The sample (Koam-Mashaal), east Rosetta, Egypt, lies on the coastal plain of the Mediterranean Sea, 15 km to the east of Rosetta mouth of the River Nile, Egypt. The study area extends for about 3.0 km along the coast, and forms 5.4 $km^2$ in surface area that is mostly covered by beach sands. The magnetic susceptibility measurements were first applied as surface field measurements. Besides, quartered 966 field samples, taken from large samples collected till a depth reaching 50 cm from the ground surface, were measured for their magnetic susceptibilities in the laboratories. The measurements of field magnetic susceptibility ($k_F$) attain their maximum value reaching about $38.0 \times 10^{-3}$ SI unit in the central northeastern part of the study area, showing a great anomaly running parallel to the shoreline. Meanwhile, the measurements of laboratory magnetic susceptibility ($k_L$) attain their maximum value reaching about $28.6 \times 10^{-3}$ SI unit in the same central NE part of the study area.

Eleven samples were selected for mineral separation and mineralogic study. This study indicates that both ilmenite and magnetite represent 87.81 % of the total economic heavy minerals in the field ($T_F$), while the remaining four economic minerals (zircon, monazite, garnet and rutile) represent only 12.9 %. An empirical polynomial equation was designed to determine the total economic heavy mineral percentage ($T_L$) in unknown black-sand placer samples, if their laboratory magnetic susceptibility ($k_L$) is known, in SI units. Besides, another empirical equation was designed to determine the ($T_F$) in unknown black-sand placer deposits, when their field magnetic susceptibilities are known, in SI units. 

## INTRODUCTION

The beach and alluvial black-sand deposits, northwestern Nile Delta, are continuing to receive attention of scientists as well as the Egyptian Government due to their content of strategic and economic heavy minerals. They contain some economic minerals that are important in nuclear power as well as metallurgical and engineering industries. The black-sands contain six main minerals accompanied by many minor ones. According to their abundances and economic importance, the six main minerals are: ilmenite, magnetite, zircon, monazite, garnet and rutile. Traces of cassiterite, gold and rare earth elements are also recorded. The main objectives of the present paper are to study and map the spatial distribution patterns of the heavy mineral concentrations in the sample area.

## LOCATION

The sample Koam Mashaal area -under study- lies on the coastal plain of the Mediterranean Sea, 15 km to the east of Rosetta mouth of the River Nile, Egypt (Figure1). It is located between longitudes 30° 322 103 E and 30° 342 083 E and latitudes 31° 262 593 N and 31° 27 2 593 N. The sample area extends for about 3.0 km along the coast, and forms 5.4 $km^2$ in surface area, that is mostly covered by beach sands.

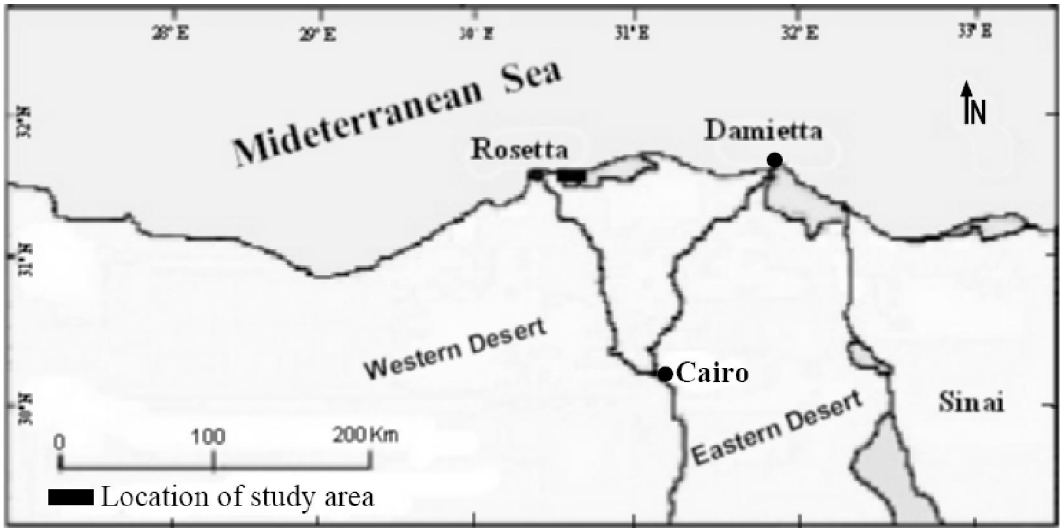


**Figure 1 : Map of northern egypt showing the location of the sample Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

## GEOLOGY

Black sand deposits in the northern Nile Delta, especially in the sample Koam Mashaal area-under study-have received the attention of several researchers, since early 20th century. These researchers include Elshazly and Wassef[10], Elhadary[7], Abu-Diab[1] and Bakheit[3]. Alaskary and Freihy[2] identified three depositional phases in the upper 30 m at Rosetta and Damietta promontories. These are from base to top: transgression, regression and erosional transgression phases. The beach is generally flat in the Rosetta area, where seawater crosses the beach during winter stormy conditions and high tide periods[6].

## MAGNETIC SUSCEPTIBILITY MEASUREMENTS

### Instrumentation

The pocket susceptibility meter, type KT-6, Geofyzika Brno, Czech Republic is designed for quick-field measurements of magnetic susceptibility of outcropping rocks, drill cores and larger pieces of rocks. It was used to determine the magnetic susceptibility in both the field and the laboratory. So, the black-sand samples were put in plastic cylindrical containers, 11 cm in diameter and of 6 cm in height, which are suitable dimensions for measuring samples in the laboratory.

The sensitivity of the equipment is $1*10^{-5}$ SI units, and the measuring ranges vary from –999 to $9999*10^{-3}$ SI units, with automatically switched accuracy: 9.99, 99.9, 999[13].

### Survey and sampling procedures

The sample Koam Mashaal area -under study- is relatively a flat terrain. The field and laboratory magnetic susceptibility measurements, beside spectrometry represent the most appropriate geophysical tools for prospecting of black-sand placer and sand-dune deposits[8,9]. Environmental magnetism deals with the magnetic properties of natural iron-oxides as a tool for understanding and interpreting the processes in sedimentary systems[11,14,15]. It has been applied successfully in modeling sediment loads in fluvial systems[5,13].

The magnetic susceptibility measurements were first applied as surface field measurements. Moreover, quartered 966 field samples, taken from large samples collected till a depth reaching 50 cm from the ground surface, were measured for their magnetic susceptibilities in the laboratory. The gathered samples were taken along equally-spaced stations, 50 m apart, at 32 parallel equally-spaced (100 m) profiles. These profiles were oriented in a N-S direction and spaced at 100 m intervals, covering an area of about 5.4 $km^2$.

A 12-channal Global Positioning System (GPS) instrument was used to set up the survey grid with a Universal Transverse Mercator (UTM) coordinate system, using the World Grid (WG84) as datum. The samples were collected from the same places, where the field magnetic susceptibility measurements were taken. The adequate form of data presentation was the filled colour contour maps for field and laboratory magnetic susceptibility measurements (Figures 2 and 3). A quick look to these maps shows a great similarity between both of them, especially for locations of the black-sand lenses.

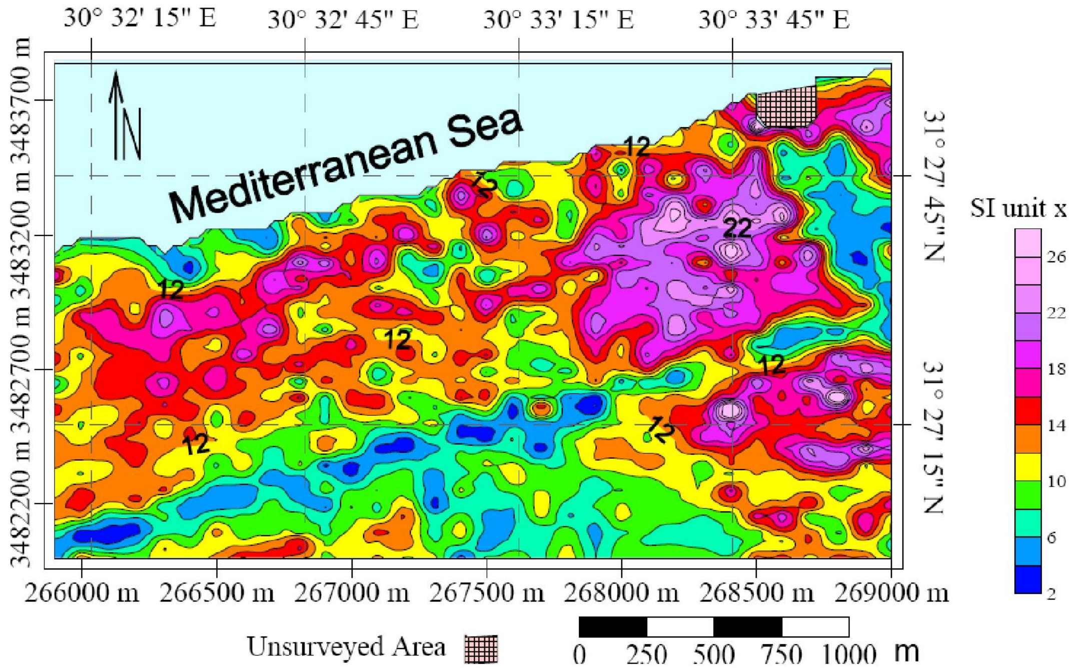


**Figure 2 : Filled-colour contour map of the field magnetic susceptibility (FMS) measurements, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**
**Contour interval = 2 SI unit x $10^{-3}$**

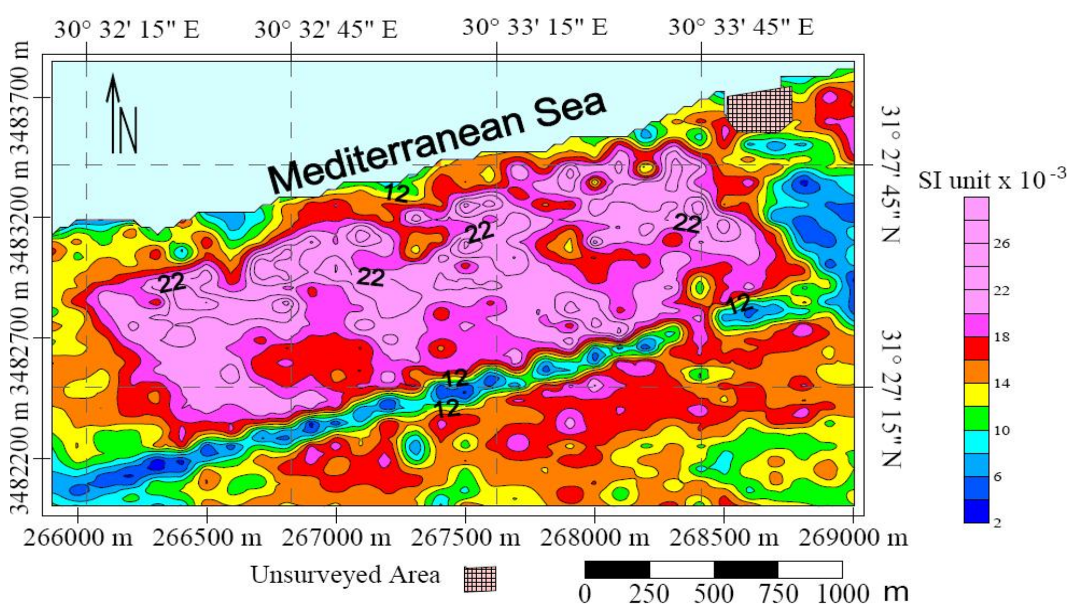


**Figure 3 : Filled-colour contour map of the laboratory magnetic susceptibility (LMS) measurements, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**
**Contour interval = 2 SI unit x $10^{-3}$**

## QUALITATIVE INTERPRETATION

### Common

Visual examination of the field and laboratory magnetic susceptibility contour maps (Figures 2 & 3) shows that the measured levels are almost the same, especially for slight variations in their shapes and locations. Some of the delineated high magnetic susceptibility anomalies are circular in shape, while others are elongated, either parallel to the Sea shore or in the NW direction. The highest levels of magnetic susceptibility are located nearly in the central part and the northeastern corner of the study area. These levels are associated with the eastern side of the major black-sand lens and Koam Mashaal old sand dunes. The lowest levels of magnetic susceptibility are located in three places: near the Mediterranean Sea shore line, the southern border of the study area and in an area of ENE-elongated contours parallel to the shore line and related to the old and dry man-excavated drainage channel. The intermediate magnetic susceptibility level is distributed allover the remaining surface of the study area.

### Field magnetic susceptibility ($k_F$)

The measurements of field magnetic susceptibility ($k_F$) attain their maximum values reaching about $38.0 \times 10^{-3}$ SI unit in the centre of northeastern part of the study area, showing a great anomaly running parallel to the shoreline. The minimum $k_F$ value reaching $1.52 \times 10^{-3}$ SI unit is situated in the central southern part of the study area, which represents an old dry man-excavated drainage channel. The average $k_F$ value in the study area reaches $12.2 \times 10^{-3}$ SI unit.

The patterns evident on the $k_F$ contour map (Figure 2) reflect the general trends of the zones of black-sand concentrations, which are well described by the elongated shapes of anomalies, clearly seen on this map. This $k_F$ contour map could be separated into three distinct zones ranging in intensity from less than $6.0 \times 10^{-3}$ SI unit to more than $18.0 \times 10^{-3}$ SI unit, and in colour from blue (low intensity) to violet (high intensity). These distinct three levels are:

(A) Low $k_F$ zone (from $1.5 \times 10^{-3}$ SI unit to $8.0 \times 10^{-3}$ SI unit)

This zone is mainly encountered at the central southern part of the study area, parallel to the Sea shore line. It coincides also with three places: the old dry man-excavated drainage channel, the southern and northern parts of the study area as well as the southern part of Koam Mashaal sand dunes. This level is shown in blue (Figure 4).

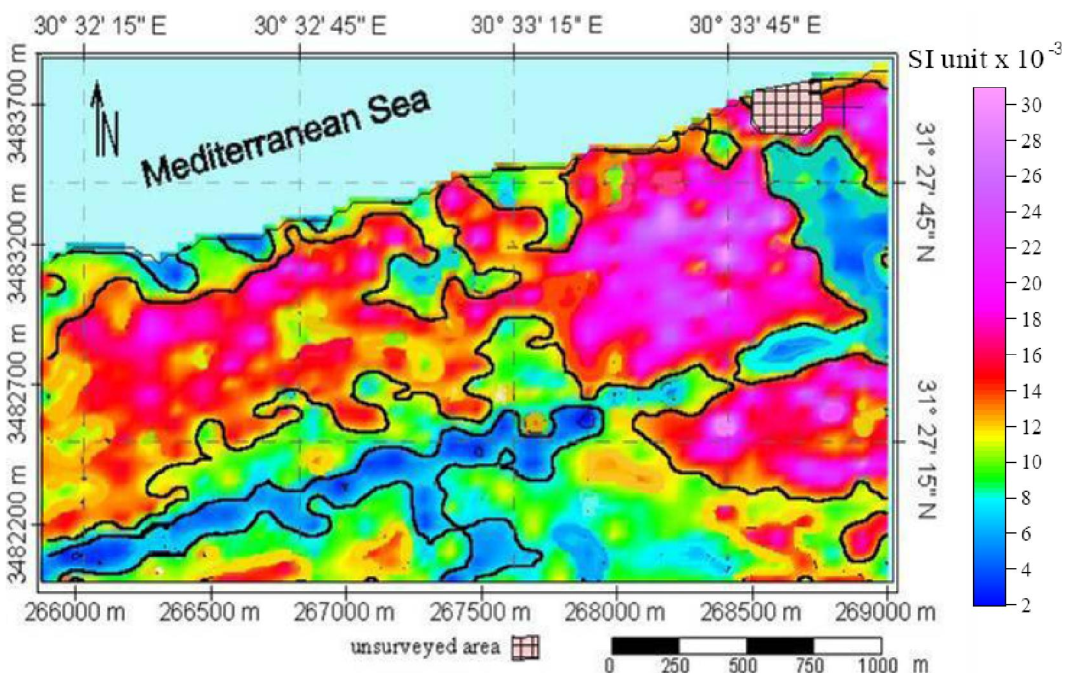


**Figure 4 : Filled colour zonation map of the field magnetic susceptibility measurements ($k_F$), Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

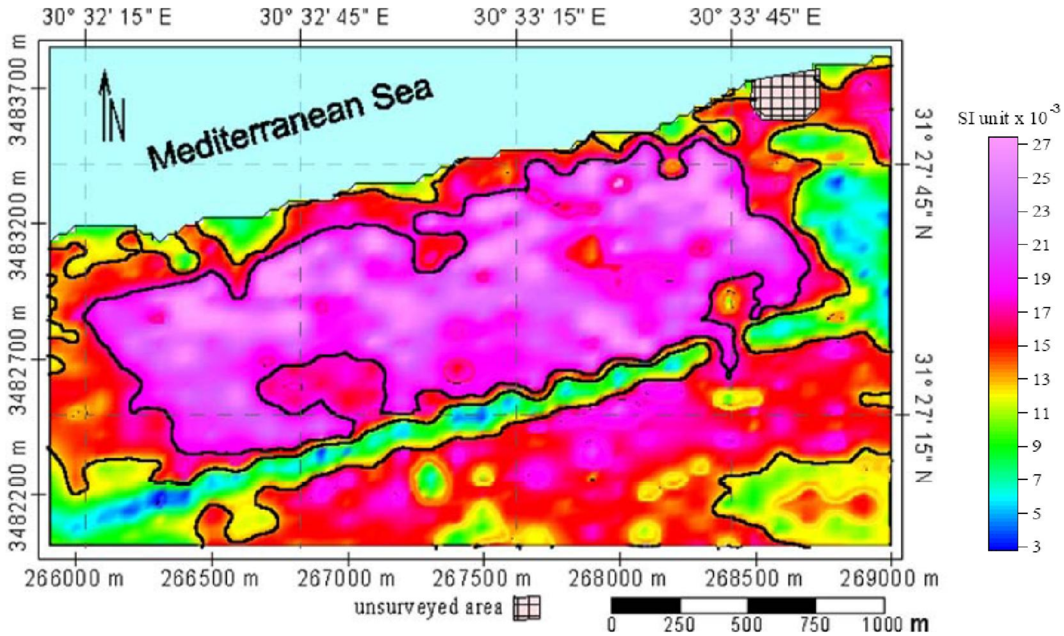


**Figure 5 : Filled colour zonation map of the laboratory magnetic susceptibility measurements ($k_L$), Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

(B) Intermediate $k_F$ level (from $8.0 \times 10^{-3}$ SI unit to $14.0 \times 10^{-3}$ SI unit)

This zone is located between the high and low $k_F$ zones. It is shown in green, dark and light yellow (Figure 4).

(C) High $k_F$ level (from $14.0 \times 10^{-3}$ SI unit to $30.0 \times 10^{-3}$ SI unit)

This zone extends over a large portion at the central northern part of the study area, parallel to the Sea shore line, with some extensions in the northwestern direction, beside a small part to its south. It also extends to Koam Mashaal sand dunes. It is shown in red and violet (Figure 4).

## Laboratory magnetic susceptibility ($k_L$)

The measurements of laboratory magnetic susceptibility ($k_L$) attain their maximum value reaching about $28.6 \times 10^{-3}$ SI unit in the central northeastern part of the area under study, in the form of a great elongated anomaly, running parallel to the Sea shoreline. The minimum $k_L$ value reaching $2.16 \times 10^{-3}$ SI unit is situated in the central southern part of the study area, which represents an old dry man-excavated drainage channel. The average value of $k_L$ in the study area reaches 15.67 $\times 10^{-3}$ SI unit.

The measurements of laboratory magnetic susceptibility $k_L$ evident on the filled colour contour map (Figure 3) could be subdivided into three relative and distinct zones, ranging in colour from deep blue (low intensity) to light violet (high intensity) to help in data interpretation (Figure 5). These three zones of $k_L$ are described hereafter:

(A) Low $k_L$ zone (from $2.2 \times 10^{-3}$ SI unit to $10.0 \times 10^{-3}$ SI unit)

This zone is encountered at the central southern part of the study area, parallel to the Sea shore line. It coincides with three places: the old dry man-excavated drainage channel, the southern and northern parts of the study area as well as the lower part of Koam Mashaal sand dunes. This level is coloured by blue (Figure 5).

(B) Intermediate $k_L$ zone (from $10.0 \times 10^{-3}$ SI unit to $16.0 \times 10^{-3}$ SI unit)

This zone is located between the high and low $k_L$ zones. It is coloured by green, dark and light yellow (Figure 5).

(C) High $k_L$ zone (from $16.0 \times 10^{-3}$ SI unit to $28.0 \times 10^{-3}$ SI unit)

This zone extends over a large portion of the study area. It is represented by an elongated anomaly, located in its central part, parallel to the Sea shoreline, with some extensions in the northwestern direction, beside a small one to its south. This zone extends also to Koam Mashaal sand dunes. It is coloured by red and violet (Figure 5).

## QUANTITATIVE INTERPRETATION

### Common

The quantitative interpretation of both field and laboratory magnetic susceptibility ($k_F$ and $k_L$) measurements are based on an attempt to determine total heavy mineral contents or concentrations ($T_F$&$T_L$) in the black-sand placer deposits from their measured ($k_F$ and $k_L$) values. A standard curve is created (Figure 7), which represents the magnetic susceptibility response of synthetic samples prepared, to fulfill this purpose.

### Preparation of synthetic samples

A relatively big surface, representative and composite black-sand placer deposit sample was performed from all the 966 samples gathered from all the measured stations of the investigated area. This composite sample was subjected to a separation process of economic (heavy) and gangue (light) mineral fractions, using the wet-table technique (Wilfly TABLE), depending on the gravitational separation. This process was carried out by the scientific and technical staff of the Ore Dressing Laboratory (ODL), Production Division, Nuclear Materials Authority (NMA).

A total of 15 synthetic samples of different total economic (heavy) mineral concentrations were prepared from the separated economic heavy and light mineral fractions. The total economic (heavy) mineral contents in these samples were accomplished to range approximately between 0 % and 90 %.

### Relation between $k_F$ and $k_L$

A bivariate correlation, drawn between $k_F$ and $k_L$ for the 966 samples (Figure 6), shows a very good correlation between both of them, with a correlation coefficient "$r_s$" attaining 0.50, where the critical value "$r_e$" reaches 0.06 at the 95% level of confidence (Geigy, 1962). A good and a direct relation between $k_F$ and $k_L$ could be observed (Figure 6 A and 6B). From this statistical relation, the following two equations could be computed.

$$k_F = 0.57 \times k_L + 3.17 \quad (1)$$

$$k_L = 0.50 \times k_F + 9.66 \quad (2)$$

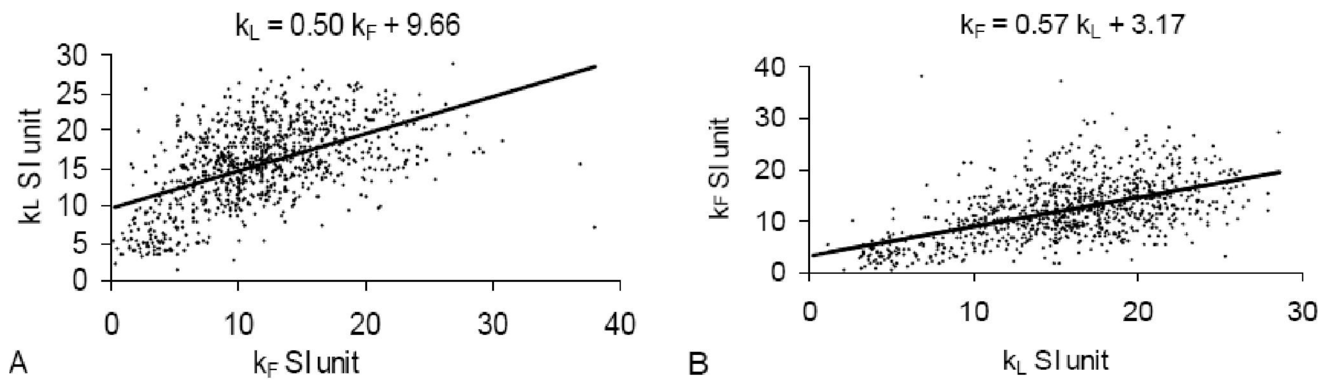


**Figure 6 : Relationship between laboratory and field magnetic susceptibility ($k_F$ and $k_L$) measurements, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

### Relationship between $k_L$ and $T_L$

Laboratory magnetic susceptibility ($k_L$) measurements were conducted for the 15 prepared synthetic samples. The relationship between the measured laboratory magnetic susceptibilities (in SI unit) and the effective economic (heavy) mineral contents ($T_L$, in %) was graphically presented in the form of a standard curve (Figure 7). This figure shows that the laboratory magnetic susceptibility ($k_L$) responses of the tested synthetic samples increase with the increase of the total economic (heavy) mineral ($T_L$) percentages. The bivariate correlation between ($k_L$) and ($T_L$) for the 15 prepared synthetic samples shows a very good correlation with a computed correlation coefficient "$r_s$" attaining 0.99 and a critical value "$r_e$" reaching 0.51, at the 95 % level of confidence (Clarke and Cooke, 1986). From this standard curve, a mathematical relation can be calculated in the form of a polynomial equation as follows:

$$T_L = 0.72\, k_L - 0.0011\, k_L^2 - 1.23 \quad (3)$$

where $T_L$ is the total economic heavy mineral content (T.E.H.M), in % as calculated from $k_L$, SI units and $k_L$

is the laboratory magnetic susceptibility measurements ($\times 10^{-3}$ SI units).

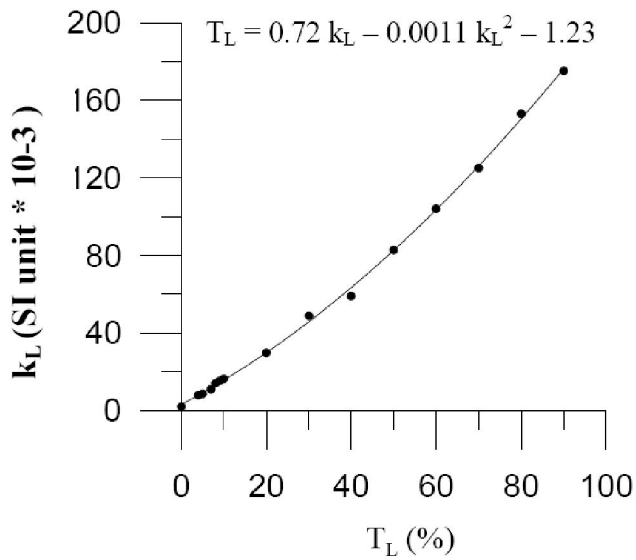


**Figure 7 : A standard curve showing the relation between the laboratory magnetic susceptibility($k_L$) measurements and the total economic heavy mineral contents ($T_L$) as calculated using $k_L$ of the 15 prepared synthetic samples of the black-sand beach deposits, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

Therefore, the polynomial equation (No. 3) relating $k_L$ and $T_L$ could be applied to determine the total economic (heavy) mineral percentages ($T_L$) in the unknown black-sand placer samples (in %), if their laboratory magnetic susceptibilities ($k_L$) are measured in SI units.

The advantage of this polynomial equation is its easiness in use as well as saving time, money and chemicals. It starts a simple way to get quick and accurate figures of $T_L$ from $k_L$ of the samples. This application gives approximate figures about the samples collected from any similar area. The obtained values are more or less comparable with the actual and real values. They can represent reliable values in the reconnaissance stage.

## Relationship b etween $k_F$ and $T_F$

From equations (2) and (3), $T_F$ related to $k_F$ can be calculated as follows:

$$T_F = 0.35\ k_F - 0.0003\ k_F^{\ 2} + 5.62 \qquad (4)$$

where $T_F$ is the total economic heavy mineral content, in %, as calculated using $k_F$, $k_F$ is the field magnetic susceptibility measurements, in SI $\times 10^{-3}$ units.

Consequently, the polynomial equation No.4 relating $k_F$ and $T_F$ can be applied to determine the ($T_F$) in the unknown black-sand placer deposits, when their field magnetic susceptibilities are measured, in SI units

Test of the Polynomial Equation relating $k_L$ & (heavy mineral content) HMC. The samples, which nearly possess the same magnetic susceptibilities, were picked up. Eleven samples were selected from the 966 samples

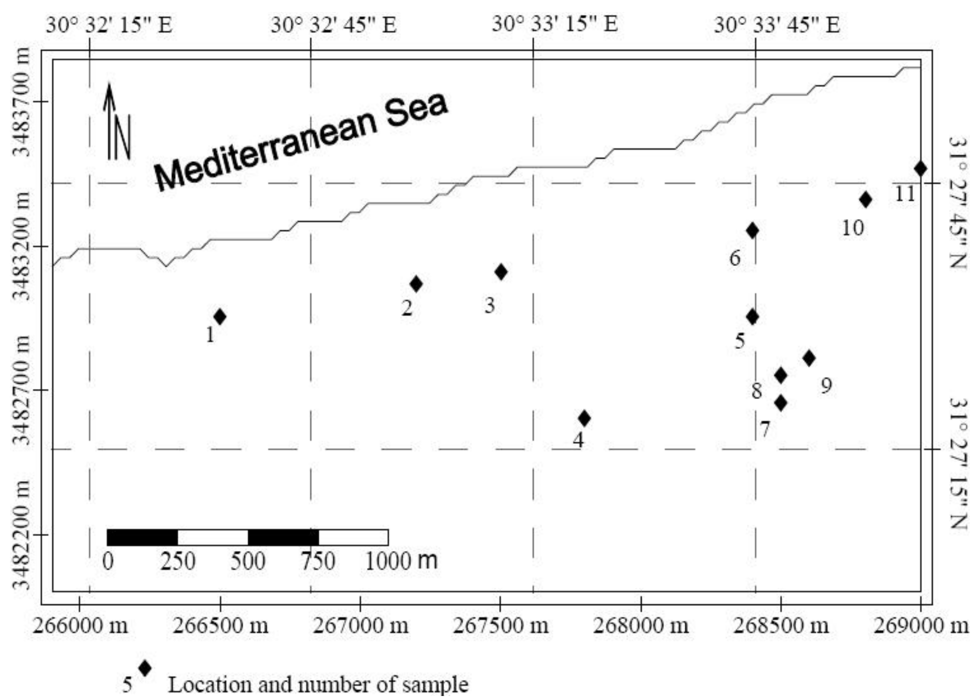


**Figure 8 : Location map of the selected, prepared, separated, fractionated and microscopically examined field samples of the black-sand placer deposits, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

(Figure 8), according to their magnetic susceptibilities, for mineral separation using heavy liquids. From heavy-liquid separation results, the polynomial equation (No.3) could be tested through its application on the laboratory measurements of magnetic susceptibilities of these eleven selected samples. The results are listed in TABLE 1. They show good compatibilities between the percentages of heavy mineral contents, as calculated using the polynomial equation (No. 3) and those determined using heavy liquids.

**TABLE 1 : Total and individual economic (heavy) minerals, in %, related to the black-sand placer deposits, as separated using heavy liquids for the eleven selected samples, collected from the field, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

| Sample Number (Figure 8) | Separated T.E.H.M. (%) | Magnetite (%) | Ilmenite (%) | Leucoxene (%) | Zircon (%) | Rutile (%) | Garnet (%) | Monazite (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | 17.458 | 7.040 | 8.323 | 0.399 | 0.852 | 0.222 | 0.622 | N. D. |
| 2 | 13.887 | 4.602 | 7.626 | 0.294 | 0.811 | 0.195 | 0.360 | 0.0015 |
| 3 | 17.515 | 6.580 | 9.317 | 0.243 | 0.736 | 0.216 | 0.423 | N. D. |
| 4 | 3.671 | 1.265 | 1.978 | 0.151 | 0.108 | 0.044 | 0.124 | N. D. |
| 5 | 9.511 | 2.610 | 5.769 | 0.268 | 0.356 | 0.144 | 0.364 | N. D. |
| 6 | 17.854 | 7.098 | 8.866 | 0.373 | 0.807 | 0.255 | 0.455 | N. D. |
| 7 | 11.221 | 3.520 | 6.158 | 0.430 | 0.446 | 0.165 | 0.501 | N. D. |
| 8 | 6.237 | 2.180 | 3.329 | 0.158 | 0.228 | 0.076 | 0.267 | N. D. |
| 9 | 3.537 | 0.988 | 1.882 | 0.192 | 0.174 | 0.059 | 0.241 | 0.0001 |
| 10 | 5.749 | 2.286 | 2.862 | 0.076 | 0.199 | 0.073 | 0.254 | N. D. |
| 11 | 12.243 | 4.921 | 5.862 | 0.236 | 0.368 | 0.140 | 0.716 | N. D. |
| $\overline{X}$ | 10.807 | 3.917 | 5.634 | 0.256 | 0.462 | 0.145 | 0.393 | 0.00014 |

**T. E. H. M. = Total economic heavy mineral content, in (%) N. D. = Not Detected $\overline{X}$ = Arithmatic mean**

Bivariate correlation, between separated and calculated total economic heavy minerals, for the eleven selected samples (Figure 9) shows a very good correlation, with a correlation coefficient "$r_s$" equals to 0.99, where the critical one "$r_e$" equals to 0.60 at the 95 % level of confidence (Clarke and Cooke, 1986). A linear relation between separated and calculated total economic (heavy) mineral percentages in the eleven selected samples was observed (Figure 9). From this statistical relation, the following equation is obtained.

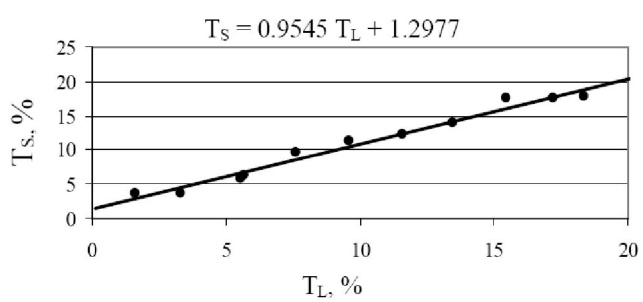


**Figure 9 : Relation between separated and calculated total economic heavy mineral content contents ($T_S$ and $T_L$) for the eleven selected samples of the black-sand placer deposits, collected from the field, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

$$\mathbf{T_S = 0.9545\ T_L + 1.2977} \qquad (5)$$

From equation (3) and (5), the following equation, relating the calculated total economic heavy mineral content $T_C$, in %, and the laboratory magnetic susceptibility, $k_L$, can be calculated:

$$\mathbf{T_C = 0.124 + 0.687\ k_L - 0.001\ k_L^2} \qquad (6)$$

where $T_S$ = Separated total economic heavy mineral content using heavy liquids, in %, and $T_C$ = Calculated total economic heavy mineral content, in %.

## INTERPRETATION OF THE RESULTS

The results of heavy liquid separation of the eleven selected black-sand samples show that, the total economic heavy mineral content varies from 3.54 % to 17.85 %, with an arithmetic mean reaching 10.81 % TABLE 1. Ilmenite mineral represents 52.64 % of the total economic heavy minerals TABLE 2. Its arithmetic mean equals to 5.63 %, as related to the total black-sand placer deposits, ranging from 1.88 to 9.32 % TABLE 1. Magnetite mineral represents 35.17 % of the total economic heavy minerals TABLE 2) and 3.92

% of the total black-sands in the selected samples, which ranges from 0.99 to 7.1 % TABLE 1. Both ilmenite and magnetite minerals represent 87.81 % of the total economic heavy minerals, while the remaining other five minerals represent only 12.19 % TABLE 2. Therefore, measurement of the magnetic susceptibility, as a significant physical property, represents an excellent tool for exploration of the black-sand placer deposits.

**TABLE 2: Individual economic (heavy) minerals in %, related to the total economic (heavy) minerals as separated using heavy liquids for the eleven selected samples of the black-sand placer deposits, collected from the field, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

| Sample Number (Figure 8) | Ilmenite (%) | Magnetite (%) | Ilmenite + Magnetite (%) | Leucoxene (%) | Zircon (%) | Rutile (%) | Garnet (%) | Monazite (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | 47.60 | 40.28 | 87.88 | 2.28 | 4.87 | 1.27 | 3.70 | N. D. |
| 2 | 54.91 | 33.14 | 88.05 | 2.11 | 5.84 | 1.41 | 2.59 | 0.011 |
| 3 | 53.21 | 37.55 | 90.76 | 1.39 | 4.20 | 1.23 | 2.42 | N. D. |
| 4 | 53.90 | 34.47 | 88.37 | 4.11 | 2.95 | 1.20 | 3.37 | N. D. |
| 5 | 60.70 | 27.47 | 88.17 | 2.78 | 3.75 | 1.52 | 3.78 | N. D. |
| 6 | 49.67 | 39.76 | 89.44 | 2.05 | 4.52 | 1.43 | 2.56 | N. D. |
| 7 | 54.87 | 31.38 | 86.25 | 3.83 | 3.98 | 1.47 | 4.46 | N. D. |
| 8 | 53.35 | 34.98 | 88.33 | 2.53 | 3.66 | 1.21 | 4.27 | N. D. |
| 9 | 53.21 | 27.94 | 81.15 | 5.42 | 4.93 | 1.68 | 6.82 | 0.004 |
| 10 | 49.78 | 39.76 | 89.54 | 1.32 | 3.46 | 1.27 | 4.42 | N. D. |
| 11 | 47.88 | 40.19 | 88.07 | 1.93 | 3.01 | 1.15 | 5.85 | N. D. |
| $\overline{X}$ | 52.64 | 35.17 | 87.82 | 2.71 | 4.11 | 1.35 | 4.02 | 0.001 |

**N. D. = Not Detected**

**TABLE 3 : Total economic heavy minerals, in %, as calculated using the polynomial equation relating $k_L$ & $T_S$ and as separated using heavy liquids, for the eleven selected samples of the black-sand placer deposits, collected from the field, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

| Sample Number (Figure 8) | $k_L$*$10^{-3}$ (SI units) | $T_S$ (%) | $T_L$ (%) | $T_S$ - $T_L$ (%) | Error (%) | $T_C$ (%) | $T_S$–$T_C$ (%) | Error (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | 24.2 | 17.46 | 15.55 | 1.91 | 10.93 | 16.14 | 1.32 | 7.55 |
| 2 | 21.2 | 13.89 | 13.54 | 0.35 | 2.50 | 14.22 | 0.33 | 2.41 |
| 3 | 26.8 | 17.52 | 17.28 | 0.24 | 1.37 | 17.79 | 0.27 | 1.56 |
| 4 | 6.41 | 3.67 | 3.34 | 0.33 | 9.01 | 4.49 | 0.82 | 22.20 |
| 5 | 12.6 | 9.51 | 7.67 | 1.84 | 19.39 | 8.62 | 0.90 | 9.41 |
| 6 | 28.6 | 17.85 | 18.46 | 0.61 | 3.41 | 18.92 | 1.07 | 5.97 |
| 7 | 15.5 | 11.22 | 9.67 | 1.55 | 13.86 | 10.52 | 0.70 | 6.21 |
| 8 | 9.73 | 6.24 | 5.67 | 0.57 | 9.07 | 6.71 | 0.47 | 7.60 |
| 9 | 4.02 | 3.54 | 1.65 | 1.89 | 53.45 | 2.87 | 0.67 | 18.87 |
| 10 | 9.6 | 5.75 | 5.58 | 0.17 | 2.93 | 6.62 | 0.88 | 15.23 |
| 11 | 18.4 | 12.24 | 11.65 | 0.60 | 4.88 | 12.41 | 0.17 | 1.39 |
| $\overline{X}$ | 16.10 | 10.81 | 10.00 | 11.62 | 11.89 | 10.85 | 0.69 | 8.95 |

**$T_S$ = Separated total economic heavy mineral content, using heavy liquids, in %.**
**$T_L$ = Calculated total economic heavy mineral content %, using equation (No. 3).**
**$T_C$ = Calculated total economic heavy mineral content %, using equation (No. 6).**

## Bivariate correlation

Bivariate correlations of each mineral content, in %, in the eleven selected samples, the calculated total economic heavy mineral content ($T_C$, in %) and the separated total economic heavy mineral content ($T_S$, in %) in the black-sand placer deposits were conducted. The correlation coefficients between each pair of these variables were estimated through the calculation of Spearman's product moment correlation coefficient "$r_s$"

TABLE 4. The reliability of the calculated values of the bivariate correlation coefficients has been checked against the critical value "$r_e$", extracted from the Statistical TABLES (Clarke and Cooke, 1986), at the 95 % level of confidence, which reached 0.60. The results of this correlation show good correlations between all mineral contents (in %) as well as between the calculated and separated total economic heavy mineral contents (in %). The least significant correlation coefficients are related with both garnet and leucoxene. Meanwhile, the other four minerals show the highest correlation coefficients (TABLE 4). Linear relations between each mineral content (in %) and the separated total economic heavy mineral content (in %) in the eleven selected samples are shown on Figure (10). From these statistical relations, the following six equations could be computed and used to determined the content of any mineral (in %), out of the significant six minerals, from the determined total economic heavy mineral content (in %), when separated using the heavy liquids (Figure 10).

**TABLE 4: Matrix of correlation coefficient "$r_s$" between the contents of the separated and calculated total economic heavy minerals ($T_S$ and $T_C$), in %, as well as the most significant six of these minerals in the eleven selected samples of the black-sand placer deposits, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

| | $T_S$ | $T_C$ | Ilmenite | Magnetite | Zircon | Garnet | Rutile | Leucoxene |
|---|---|---|---|---|---|---|---|---|
| $T_S$ | 1.00 | | | | | | | |
| $T_C$ | 0.99 | 1.00 | | | | | | |
| Ilmenite | 0.98 | 0.97 | 1.00 | | | | | |
| Magnetite | 0.97 | 0.98 | 0.94 | 1.00 | | | | |
| Zircon | 0.91 | 0.90 | 0.91 | 0.89 | 1.00 | | | |
| Garnet | 0.75 | 0.74 | 0.72 | 0.82 | 0.74 | 1.00 | | |
| Rutile | 0.96 | 0.95 | 0.96 | 0.93 | 0.95 | 0.72 | 1.00 | |
| Leucoxene | 0.69 | 0.67 | 0.72 | 0.68 | 0.82 | 0.72 | 0.82 | 1.00 |

**$T_S$ = Separated total economic heavy mineral contents, using heavy liquids, in %.**
**$T_C$ = Calculated total economic heavy mineral contents, in %.**
**$r_e$ = Critical correlation coefficient (= 0.60), at the 95 % level of confidence.**

**Ilmenite % = 0.495 $T_S$ +0.283 (7)**

**Magnetite % = 0.405 $T_S$ -0.460 (8)**

**Zircon % = 0.049 $T_S$ - 0.072 (9)**

**Garnet % = 0.023 $T_S$ +0.147 (10)**

**Rutile % = 0.013 $T_S$ +0.004 (11)**

**Leucoxene % = 0.015 $T_S$ +0.099 (12)**

where $T_S$ = Separated total economic heavy mineral content, in %.

It worths to mention that the validity of the obtained linear equations (from 7 to 12) is restricted only to the studied black-sand placer deposit of Koam Mashaal area as well as similar deposits and similar environments, since local variations in the mineralogical characteristics and sedimentation conditions could change these percentages and, therefore, should be taken into consideration.

## SUMMARY AND CONCLUSIONS

The present study deals with the analysis and interpretation of the results of both field and laboratory magnetic susceptibility measurements conducted on a sample area, east Rosetta, Egypt. The outcome of these analyses and interpretations were used to define the spatial distribution of the zones of heavy (economic) mineral concentrations. The magnetic susceptibility measurements were conducted, both in the field and in the laboratory, for 966 samples quartered from large samples collected from depths reaching 50 cm.

The visual examination of the field and laboratory magnetic susceptibility contour maps shows that the measured levels on both (field and laboratory) maps are nearly the same, especially for their shapes and locations. The highest levels are located near the Mediterranean Sea shore, at the southern border of the study (sample) area and in an area of ENE-trending contours, parallel to the shore line. Bivariate correlation conducted between the field "F" and laboratory "L" magnetic susceptibilities ($k_F$ and $k_L$) for the 966 samples shows a very good correlation between both of them, at the 95 % level of confidence.

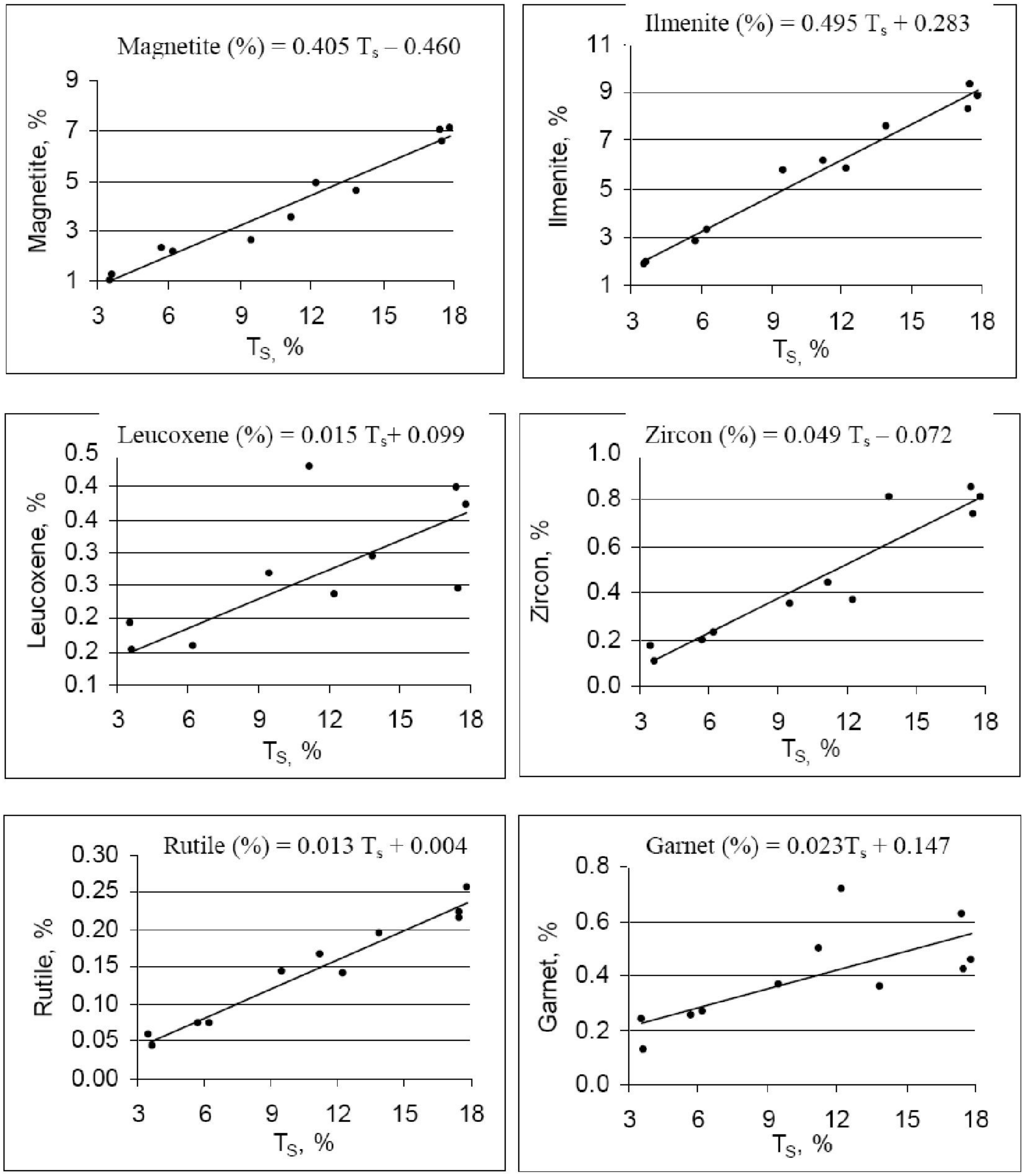


**Figure 10 : Scatter plot relating each mineral percentages and total economic heavy mineral ($T_S$) percentages, separated using heavy liquids, for the eleven selected samples, black-sand placer deposits, Koam-mashaal area, East rosetta, Mediterranean Sea coast, Egypt.**

A total of 15 synthetic samples of different total economic (heavy) mineral concentrations were prepared from the separated economic heavy and light mineral fractions. The total economic (heavy) mineral contents in these samples were produced to range approximately from 0 to 90 %. Two mathematical relations were computed in the form of two polynomial equations, which can be applied to determine the unknown total economic (heavy) mineral percentages, from their known field and/or laboratory magnetic susceptibility measurements.

Eleven samples were selected from the 966 samples, according to their magnetic susceptibility measurements for mineral separation and mineralogic study. Heavy liquid separation and magnetic fractionation were carried out on these eleven samples. The total economic heavy mineral content were found to vary from 3.54% to 17.85%, with an arithmetic mean of 10.81%. Ilmenite represents 52.64 %, on the average, from the total economic heavy minerals. Its arithmetic mean equals 5.63 %, from the total black-sand placer deposits, ranging from 1.88 % to 9.32 %. Magnetite represents 35.17

%, on the average, from the total economic heavy minerals and 3.92 % from the total black-sands placer deposits, which ranges from 0.99 % to 7.1 %. The two minerals (ilmenite and magnetite) represent 87.81 %, on the average, from the total economic heavy minerals, while the remaining other five heavy (economic) minerals represent only 12.19 %, on the average.

Bivariate correlation between the mineral percentages in these eleven selected samples, the calculated total economic heavy mineral percentages and the separated total economic heavy mineral percentages in the black-sand placer deposits were conducted. The results of these correlations show significant values between all mineral percentages as well as the calculated and separated total economic heavy mineral percentages. The linear relations (equations) between each individual mineral content and the separated total economic heavy mineral content were calculated. These equations could be used to determine the percentage of any mineral, out of the significant six minerals, from the determined total economic heavy mineral percentages as separated using heavy liquids, as for as this area of study is concerned.

## REFERENCES


**[1]** A.A.Abudiab; Sedimentological studies and economic evaluation of the coastal sand dunes between Elgadia and Idko, Rosetta, Egypt. M. Sc. Thesis (Unpub.), Faculty of Science, Mansuora University, Mansuora, Egypt, 137 **(2001)**.

**[2]** M.A.Alaskary, O.E.Freihy; Depositional phases of Rosetta and Damietta promontories on the Nile Delta coast. Journal of African Earth Sciences, Great Britain, **5(6)**, 627-633 **(1986)**.

**[3]** A.F.Bakheit; Mineralogy and concentration of economic heavy minerals, northern Delta, Egypt. Ph. D. Thesis.(Unpub.), Institute of African Research and Studies, Cairo University, Geiza, Egypt, 131 **(2004)**.

**[4]** G.M.Clarke, D.Cooke; A basic course in statistics. English Language Book Society (ELBS) Edward Arnold (Publishers) Ltd, London, Great Britain, Second edition, 421 **(1986)**.

**[5]** J.A.Dearing; Natural magnetic tracers in fluvial geomorphology, In: Foster, I.D.L. Edition, Tracers in Geomorphology, John Wiley and Sons, London, 57-82 **(2000)**.

**[6]** A.F.Elhadary; Geologic and radiometric investigations on Abu-Khashaba deposits, east Rosetta, Egypt. M. Sc. Thesis (Unpub.), Faculty of Science, Cairo University, Geiza, Egypt, 150 **(1988)**.

**[7]** A.F.Elhadary; Geological, sedimentological and radiometric studies on the black-sand deposits, west Rosetta beach, with emphasis on the heavy economic minerals. Ph. D. Thesis (Unpub.), Faculty of Science, Cairo Universty, Geiza, Egypt, 184 **(1998)**.

**[8]** S.A.Elkhateeb; Geophysical evaluation of some sand beach and alluvial deposits in northeastern Africa. Unpub. M.Sc. Thesis, institute of African research and studies, Cairo University, Giza, Egypt, 190 **(2005)**.

**[9]** M.A.El-Sadek and S.A.Elkhateeb; Magnetic susceptibility of black-sand beach deposits, Koam Mashaal area, east Rosetta, Egypt. Internal Report Series, NMA-IRS-3/2002, Cairo, Egypt, 27 **(2002)**.

**[10]** E.M.Elshazly, S.N.Wassef; Ground radiometric surveying as a tool for heavy mineral content exploration in Mediterranean beach sands of the Nile derivation, Egypt.J.Geol., **28**, 283-289 **(1984)**.

**[11]** M.E.Evans, F.Heller; Environmental Magnetism: Principles and applications of enviromagneticsK, Academic Press, London, 382 **(2003)**.

**[12]** J.R.Geigy; Documeenta Geigy Scientific TABLES 6th edition, by Konard Diem, Published by J.R.Geigy, S.A.Basle, Switzerland, 778 **(1962)**.

**[13]** Geofyzika Brno; Instruction manual of kappa meter KT6, Geofyzika Brno, Brno, Czech Republic, 29 **(1998)**.

**[13]** J.Lees; Evaluating magnetic parameters for use in source identification, classification and modelling for natural and environmental materials. In: J.Walden, F.Oldfield and J.P.Smith Edition, Environmental Magnetism: A Practical Guide. Quaternary Research Association, Cambridge, 113-138 **(1999)**.

**[14]** B.A.Maher, R.Thompson, M.W.Hounslow; Introduction In: B.A.Maher, R.Thompson (Edition), Quaternary Climates, Environments and Magnetism. Cambridge Univ.Press, Cambridge, 1-48 **(1999)**.

**[15]** R.Thompson, F.Oldfield; Environmental magnetism, Allen and Unwin, London, 227 **(1986)**.