GEOPHYSICAL PROSPECTION OF IRON-TITANIUM OXIDE (ILMENITE) USING MAGNETIC METHOD IN MAGAONI, KWALE COUNTY, KENYA.

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A thesis submitted in partial fulfilment of the requirements for the award of the degree of Master of Science (Physics) in the School of Pure and Applied Sciences of Kenyatta University.

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DECLARATION

This thesis is my original work and has not been presented for the award of a degree or any other award in any University.

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DEDICATION
This thesis is dedicated to Donata
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TABLE OF CONTENTS

Table of Contents

DECLARATION............................................................................................................... ii
DEDICATION.................................................................................................................. iii
ACKNOWLEDGEMENTS ................................................................................................. iv
TABLE OF CONTENTS .................................................................................................... vi
LIST OF TABLES ............................................................................................................. ix
LIST OF FIGURES ...................................................................................................... x
LIST OF ABBREVIATIONS ........................................................................................ xii
ABSTRACT .................................................................................................................. xiii

CHAPTER ONE

INTRODUCTION............................................................................................................. 1
1.1 Background to the study ....................................................................................... 1
1.2 Study area............................................................................................................. 1
1.3 Geology of Magaoni .......................................................................................... 3
1.4 Statement of research problem ........................................................................... 5
1.5 Objectives of the research project ....................................................................... 6
  1.5.1 Main objective .............................................................................................. 6
  1.5.2 Specific objectives ....................................................................................... 6
1.6 Rationale of the study ......................................................................................... 7
4.1.1 Introduction .................................................................................................................. 23
4.2 Field equipment ............................................................................................................... 24
4.2.1 Global positioning system .......................................................................................... 24
4.2.2 Flux Gate Magnetometer ............................................................................................ 24
4.3 Field measurements ....................................................................................................... 25
4.4 Magnetic data correction ............................................................................................... 25
4.4.1 Diurnal variations corrections .................................................................................... 25
4.4.2 Geomagnetic field correction ...................................................................................... 27
4.5 Data enhancement .......................................................................................................... 27
4.5.1 Trend analysis ............................................................................................................ 27
4.5.2 Reduction to the pole ................................................................................................. 30
4.5.3 Vertical and horizontal derivative ............................................................................... 30
4.5.4 Euler deconvolution ................................................................................................. 30
4.6 Chemical analysis of samples ....................................................................................... 31
4.6.1 Titanium .................................................................................................................... 31
4.6.2 Iron (III) Oxide .......................................................................................................... 32
4.6.3 Energy Dispersive X-Ray Fluorescence Spectroscopy ............................................. 32

CHAPTER FIVE

RESULTS AND DISCUSSION ................................................................................................. 35
5.1 Introduction .................................................................................................................... 35
5.2 Interpretation of Magaoni magnetic anomaly map ....................................................... 36
5.3 Interpretation of magnetic data along profiles ............................................................. 39
CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS .................................................. 53

6.1 Introduction .......................................................................................... 53

6.2 Conclusions ....................................................................................... 53

6.3 Recommendations ............................................................................. 54

REFERENCES ............................................................................................. 55

APPENDIX I: BS DIURNAL CURVES......................................................... 58

APPENDIX II: PROFILE GRAPHS............................................................ 64

APPENDIX III: SOIL SAMPLE PLATES..................................................... 70
LIST OF TABLES

Table 3.1: Basic patterns of alignment of atomic magnetic moments 21

Table 5.1: Analysis result for sample SS13 47

Table 5.2: Analysis result for sample SS16 48

Table 5.3: Analysis result for sample SS20 48

Table 5.4: Analysis result for sample SS21 49

Table 5.5: Analysis result for sample SS24 49

Table 5.6: Chemical analysis result from ODP 52
# LIST OF FIGURES

Figure 1.1: Location map of Magaoni 2  
Figure 1.2: Geological map of Southern Kenyan coast. 3  
Figure 3.1: Earth’s magnetic field vector diagram 16  
Figure 4.1: Diurnal curve for day seven of the study 26  
Figure 4.1a: Graph of profile AA’ with regional 29  
Figure 4.2b: Graph of profile AA’ without regional 29  
Figure 5.1: Magnetic Intensity colour contour map of the study area 36  
Figure 5.2: Magnetic Intensity contour map with profiles for the study area 37  
Figure 5.3: 3D Magnetic Anomaly map for the study area 38  
Figure 5.4: Euler depth solutions along profile AA’ 40  
Figure 5.5: Euler depth solutions along profile BB’ 41  
Figure 5.6: Euler depth solutions along profile CC’ 42  
Figure 5.7: Euler depth solutions along profile DD’ 42  
Figure 5.8: Euler depth solutions along profile EE’ 43  
Figure 5.9: Euler depth solutions along profile FF’ 44  
Figure 5.10: Euler depth solutions along profile GG’ 45
LIST OF ABBREVIATIONS AND ACRONYMS

2D Two-Dimension

AC Alternating Current

$B_H$ Horizontal component of geomagnetic field

BS Base Station

$B_T$ Total magnetic intensity vector

$B_z$ Vertical component of geomagnetic field

C.V Corrected Value

DC Diurnal Correction.

EDXF Energy Dispersive X-Ray Fluorescence

GPS Global Positioning System

IGRF International Geomagnetic Reference Frame

M.V Measured Value

RTP Reduced to the Pole

USGS United States Geophysical Survey

XRF X-Ray Fluorescence
ABSTRACT

The geology of Magaoni area is associated with the presence of heavy minerals. Magaoni neighbours Maumba and Nguluku where ilmenite was discovered by Tiomin Resource Inc. in 1996, using drilling and chemical analysis. Ilmenite mineral is known to be magnetically weak, but provides observable magnetic response. In this study, ground magnetic survey method was carried out to map magnetic anomalies of established stations, associated with ilmenite bearing formations. Energy Dispersive X-Ray Spectroscopy was also done on soil samples collected randomly from the study area to determine the percentage iron and titanium oxides, with an objective of supporting the magnetic method findings. The magnetic contour map plotted showed weak and shallow magnetic signatures spread throughout the study area. 2D Euler deconvolution solutions revealed presence of magnetised formations from near surface to a maximum depth of about 450 m at some points. The near surface weak magnetic formations indicated presence of ilmenite. The results from X-Ray Spectroscopy showed elevated values of titanium dioxide, ranging from 1.5 % to 13 % which is way above the global average of about 0.7 %. The percentage iron oxide was low, ranging from 1.5 % to 4 %, this being the reason for weak magnetisation of the study area. Both the geochemical and geophysical findings clearly indicate that ilmenite is present in Magaoni. Mining can commence once a confirmation survey has been undertaken using another geophysical technique such as gravity method.
CHAPTER ONE
INTRODUCTION

1.1 Background to the study
Ilmenite is iron-titanium oxide (Fe$\text{TiO}_3$) mineral which is iron-black or steel-grey in colour. It is mineral sand found either on the primary rock or sedimentary deposits along shorelines or several kilometres off the shoreline. Ilmenite from sedimentary deposits is the commonly explored due to the easy accessibility and low mining costs. Most mineral sand deposits being mined today were formed during the Holocene and Pleistocene period but some date back to Eocene (Shepherd, 1987). It is one of the 60 minerals in which titanium occurs, just like rutile, anatase, zircon, brookite etc. It is weakly magnetic but produce observable magnetic responses. Ilmenite is opaque with no cleavage; it has metallic or submetallic lustre and its specific gravity ranging between 4.7 to 4.8. Ilmenite crystallizes in the trigonal system; the ilmenite structure is an ordered derivative of the corundum structure. It is one of the heavy minerals that occur as separate 0.1 to 1.0 mm grains, containing locally few silicate inclusions, magnetite occur as smaller grains around ilmenite lamella (Jokinen, 1999).

1.2 Study area.
The study area, Magaoni is located about 50 km south of Mombasa, off Ukunda-Lunga Lunga road, the area lies within the coordinates $4^\circ 22'S$ $39^\circ 21'E$ and $4^\circ 25'S$ $39 23'E$(Figure 1.1). Ilmenite (Iron-Titanium oxide) and other heavy minerals bearing areas was explored and mapped by Tiomin Company in Maumba and Nguluku, a few kilometres from Magaoni, Kwale County. Base Titanium Company is currently mining and exporting ilmenite, rutile and zircon.
Magaoni area and the mining sites being in Kwale region have similar geological setting and was therefore considered likely that heavy minerals, especially ilmenite and rutile are present in the area. The study was conducted in this area to establish the extent of ilmenite distribution in Kwale County.

Figure 1.1 Location map of the study area within the map of Kenya.
1.3 Geology of Magaoni

The area lies within the Magarini sands formation which forms a belt of low hills parallel to the coast. The mineralisation of Kwale region lies within stratified Aeolian sands of the Magarini formation and consists mainly sand, with silicate and ilmenite as a dominant minerals, rutile and zircon, deposited in dunes as shown in figure 1.2. The deposit forms a belt of low hill running parallel to the coast. The area contains a silt fraction varying from 15 to 30 %. (Miller, 1952).

Figure 1.2: Geological map of Magaoni modified from geological map of Southern Coastal Kenya (Horkel, 1984).
The sands were deposited by wind action as coastal dunes after conditions of intense erosion causing heavy minerals, mainly ilmenite, rutile and zircon to be locally concentrated (Miller, 1952). Erosion prevailed during the tertiary until the upper Pliocene, when tectonic reactivation resulted in increased erosion from structural highs (Miller, 1952). Fluviatile pebble beds, gravels and sands of the Magarini formation were deposited on down-faulted and eroded Jurassic and Duruma sediments. After a regression during the lowest Pleistocene, dunes which form the bulk of the Magarini formation were blown-up. The rocks exposed consist of sediments ranging in age from Permo-Carboniferous deposition. Igneous and pyroclastic are confined to Jombo Hill, an alkaline intrusion, and associated satellite vent agglomerates and dykes (Miller, 1952).

The Duruma Sandstone Series, which is in the Kenyan correlative of the Karroo System of South and Central Africa, consists of grits, sandstones and shales that have yielded Permain and Triassic fossils, although it is possible that the series ranges down-wards to Upper Carboniferous and upwards to the Lower Jurassic. The series is divisible into three broad lithological units with coarse sandstones and grits at the top and bottom of the succession, and a finer sandstones and shales in the middle. For the most part the beds were deposited under lacustrine or sub-aerial conditions, the material having been derived from the Basement System rocks further, west. A marine intercalation in the lower part of the succession is known from evidence obtained in a deep borehole drilled near Maji-ya-Chumvi. General stratigraphic sequence is composed of brown sand at the surface followed by orange or reddish sand becoming more beige or pinkish at depth. The base of the deposits is weathered sandstone from the basal formation (Miller, 1952).
The generally close relationship of continental rifting with alkaline magmatism is documented at the southern Kenyan coast by the Jombo-Mrima alkaline complex, tentatively dated as cretaceous. The major alkaline intrusion of Jombo Hill and Dzirihini, consist of nepheline syenite surrounded by mafic alkaline rocks (malignites, jolites, melfeigite, juvite and foyaites). Associated with them are the carbonatite complexes forming Mrima Hill as well as agglomerate vents, kimberlite diatremes and minor volcanic vents. The geology of the Kenyan south coast is a major factor in the occurrence of heavy mineral sands. The heavy mineral sands occur in various parts of the coast in almost similar geological environments. Geochemically, mineral sand deposits contain ilmenite, rutile, zirconium as well as other minerals and trace elements that could be of radioactive nature, such as thorium. (Miller, 1952).

1.4 Statement of research problem
Magaoni area is located on the southern part of Kwale County, Kenya. The area is significant due to the presence of sedimentary deposits associated with heavy minerals. Magaoni area is close Maumba and Nguluku, which contain economically viable concentration of heavy minerals such as ilmenite and zircon, as mapped by Tiomin Company using mineral assemblage method. Due to the increase in demand for titanium and titanium pigment in industrial processes worldwide and the need to improve the living standards of the locals and the economy of the country, it’s therefore necessary for research to be undertaken in this area, to increase the number of sites of ilmenite deposits.
This study used ground magnetic method to determine the extent of Ilmenite deposit in Kwale County because the method is quite affordable and can be used to cover a large area. Ilmenite is a magnetic mineral and therefore magnetic method was the best geophysical technique for its prospection. The study was done in order to give recommendation on the possibility of large scale mineral sand exploration and eventual mining. This will supplement the tonnage of Ilmenite being mined by Base Titanium Company, which will definitely attract investors to open titanium processing Industries in the country. That will translate to more revenue to the country and more job opportunities to the citizens.

1.5 Objectives of the research project

1.5.1 Main Objective

To determine the lateral extension of the iron-titanium oxide (ilmenite) deposits in Kwale County through the application of ground magnetic method.

1.5.2 Specific Objectives

The specific objectives of this study were:

(i) To conduct a ground magnetic measurements in Magaoni area, Kwale County.

(ii) To carry out chemical analysis of randomly sampled surface soil samples to determine mineral oxides content.
1.6 Rationale of the study

The information of availability of ilmenite (iron titanium oxide) bearing sand is an important reason for resource assessment. This can provide a possibility of a high profile large scale prospection and mining of ilmenite, which will in turn encourage the creation of titanium processing industries, which will mean more employment opportunities and economic development of the area and the country as a whole.
CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction
Magnetic method is a geophysical survey technique that exploits the considerable differences in the magnetic properties of minerals with ultimate objective of characterising the Earth’s subsurface. The technique requires the acquisition of measurements of the amplitude of the magnetic field at discrete points along survey lines distributed regularly throughout the mineral prospect area. The technique has been used successfully in the prospection of weak, moderate and strong magnetic minerals. The method has been used to directly and indirectly delineate the mineral ore body in the prospect area.

2.2 Prospection of strong magnetic mineral ores
Magnetic method is considered the most reliable and cheap technique in the prospection of magnetically strong minerals, this is because the method locates the ores. Areas with strong magnetic minerals bearing rocks will give high and positive magnetic anomalies. Mineral ore such as magnetite, gives high and positive magnetic anomaly during prospection because of it being a strong magnetic mineral. For instance in Meru County, Kenya, magnetics was successfully used to map out iron ore deposits (magnetite). The total magnetic field data acquired from the study area, showed high magnetic signatures around magnetite bearing formations (Mustafa, 2010).

In Central Java Indonesia, magnetic method was used to directly map magnetite bearing formations. Magnetometer and susceptibility meter were used in the survey. The meters gave
high values of total magnetic field intensity and magnetic susceptibility respectively, indicating presence of magnetite (Yulianto, 2002).

2.3 Prospection of weak and non-magnetic mineral ores

Magnetic method has also been used with great success in the exploration of weak and non-magnetic minerals. The weak and non-magnetic signatures give very sharp magnetic contrast which provides anomalies that can be used indirectly to locate the mineral ores. Example of weak magnetic mineral ores is ilmenite, while for the non-magnetic are rutile, pyrite, and gold among others. Ilmenite was explored and mapped using this technique in several countries, as discussed in the next subtopic. In Hired Iran, magnetic method was used delineate host rocks of gold ore which are non-magnetic. Based on the sharp magnetic contrast, magnetic method survey revealed large anomalies. Further investigation with chemical analysis showed the source of the anomalies was pyrrholite along with gold (Haidaria, 2009).

2.4 Ilmenite prospection

Ilmenite gives a weak but observable magnetic responses, it has a magnetic susceptibility whose intensity allows the detection by magnetometers. The average value of magnetic susceptibility of ilmenite is 0.0018 SI (Telford, et al., 1976). The host rocks of ilmenite, granite, granodiorite and monazite have low magnetic susceptibility, creating a magnetic contrast which makes magnetic method suitable for its prospection. The method can be more effective when combined with either gravity method or radiometry or chemical analysis of samples from the study area (McEnroe, 1997).
In Brazil, at the delta of the Paraiba do Sul River, north of the Rio de Janeiro state, magnetic method was used to prospect ilmenite. The magnetic survey was conducted to measure the Total magnetic field of the earth using a magnetometer type GSM-19TG. The study was conducted through profile NW – SE direction, traversed to the direction of advancement of an active mining. The profiles were spaced 20m from one another with stations spaced 5m. In the 21 surveyed profiles, 955 measurements were performed. The analysed results showed consistence with ilmenite. Kappa meter KT9 was used to measure magnetic susceptibility of samples of ilmenite and it showed a mean value of 0.002 SI, which is within the range of ilmenite. In Finland, at Loivusaarenneva and Kairineva, ilmenite deposits were mapped using magnetic method. Therefore, ilmenite can be prospected by magnetic method since it is a predominant carrier of magnetic signature just like other iron-titanium oxides. (Karkkainen, 1999a).

2.5 Ilmenite exploration in Kwale County

Exploration was done from 1997 by Tiomin Resource Inc. and three dunes were mapped out in Maumba and Nguluku. The dunes were named, Central, South and North dunes, with high concentration of ilmenite, rutile and zircon. The company used geological and geochemical methods in the exploration, it involved drilling to get samples at different depths and locations. The samples were taken to the laboratories for analysis of ilmenite, rutile and zircon ores. Samples were screened and then subjected to a heavy mineral float/sink technique using heavy liquids; tetra-bromo-ethane (TBE with a SG of 2.92-2.96 gcm$^{-3}$). The resulting Heavy Mineral Concentrate was then dried and weighed. The samples were then subjected to magnetic separation using Carpco magnetic Capturing various magnetic nonmagnetic fractions which were then subjected to XRF analysis (Tiomin Resource Inc., 2000).
The XRF analysis was used to calculate by formula and ratios, the percentage of mineral species that constitute the valuable and non-valuable Heavy Mineral. Several surface and auger sampling spaced 10 km apart were completed across the width of the survey areas. Total Heavy Mineral contents of the samples collected ranged from 1.8 % up to 14.6 %, ilmenite valued up to 10.6 % and 0.94 % non-magnetic mineral including rutile and zircon. Central dune measures 2 km length, 1.25 km width and average thickness of 29 m, 5.7 % Heavy Mineral Concentration. The South dune is 4.5 km long, 600-800 m wide and average thickness of 19 m and 3.5 % HMC. Finally, North dune extends 2 km in length, 500-1000m and 66 m thick and 2.1 % THM (Tiomin Resource Inc., 2000).
CHAPTER THREE
THEORETICAL BACKGROUND

3.1 Introduction

The purpose of magnetic surveying is to identify and describe regions of the Earth’s crust that have unusual (anomalous) magnetizations. In the realm of applied geophysics the anomalous magnetizations might be associated with local mineralization that is potentially of commercial interest, or they could be due to subsurface structures that have a bearing on the location of geothermal heat source or even oil deposits. The magnetic method involves the measurement of the Earth’s magnetic field at predetermined points, correcting the measurements for known changes and comparing the resultant value of the field with expected value at each measurement station. Magnetism, like gravity, is a potential field. Anomalies in the earth’s magnetic field are caused by induced or remanent magnetism. Induced magnetic anomalies are the result of secondary magnetisation induced in a ferrous body by the earth’s magnetic field. The shape, dimensions, and amplitude of an induced magnetic anomaly is a function of orientation, geometry, size, depth, and magnetic susceptibility of the body as well as the intensity and inclination of the Earth’s magnetic field in the survey area (Merrill et al., 1996).

For exploration work, the Earth’s Main Field acts as the inducing magnetic field. This is a relatively small portion of the observed magnetic field that is generated from magnetic sources external to the earth. This field is believed to be produced by interactions of the Earth's ionosphere with the solar wind. Hence, temporal variations associated with the external magnetic field are correlated to solar activity. When describing temporal variations of the magnetic field, it is useful to classify these variations into one of three types depending on their rate of occurrence.
and source. There are three temporal variations: Secular Variations - These are long-term (changes in the field that occur over years) variations in the main magnetic field that are presumably caused by fluid motion in the Earth's Outer Core. Because these variations occur slowly with respect to the time of completion of a typical exploration magnetic survey, these variations will not complicate data reduction efforts (Doel and Cox, 1967).

Diurnal Variations - These are variations in the magnetic field that occur over the course of a day and are related to variations in the Earth's external magnetic field. This variation can be on the order of 20 to 30 nT per day and should be accounted for when conducting exploration magnetic surveys. Magnetic Storms - Occasionally, magnetic activity in the ionosphere will abruptly increase. The occurrence of such storms correlates with enhanced sunspot activity. The magnetic field observed during such times is highly irregular and unpredictable, having amplitudes as large as 1000 nT (Wright, 1981).

Exploration magnetic surveys should not be conducted during magnetic storms. This is because the variations in the field that they can produce are large, rapid, and spatially varying. Therefore, it is difficult to correct for them in acquired data. Magnetised materials produce magnetic field around themselves and if they are close to the Earth’s surface, their magnetic field combine with the earth’s field. Magnetised matter contains a distribution of microscopic magnetic moments. Magnetisation $J$ is defined as the magnetic dipole moment per unit volume of the material. Induced magnetisation $J_I$ is the component of magnetisation produced in response to an applied field. Remanent magnetisation or remanence $J_R$ is ‘permanent’ magnetisation that remains when
magnetising field is removed and essentially unaffected by weak fields. Total magnetisation is the vector sum of the induced and remanent magnetisation (Reeves, 1989).

\[ J = J_I + J_R \]  \hspace{1cm} 3.1

For sufficiently weak fields, such as the geomagnetic field the, the induced magnetisation is approximately proportional to the applied field. The constant of proportionality is known as susceptibility, \( \kappa \), magnetic susceptibility is the measure of the degree to which a substance may be magnetised (Wasilewski, 1973). If the applied field is F.

\[ J_I = \kappa F; \quad J = \kappa F + J_R \]  \hspace{1cm} 3.2

The Koenisberger ratio (Q) is a convenient parameter for expressing the relative importance of remanent and induced magnetisation, it’s given by;

\[ Q = \frac{J_R}{J_I} \]  \hspace{1cm} 3.3

### 3.2 The Geomagnetic field

This is the magnetic field of the earth, which can be measured at any part on the earth’s surface. The magnetic field on the earth at a given place and time may be considered to consist of three parts. These are the main field which is slowly changing, a diurnal part that changes with time which is approximately repeated in daily cycles and the anomaly part caused by inhomogeneity of the earth’s crust. The main field is the undisturbed component of the earth’s field which to the first approximation can be mathematically represented as a dipole field.
The best fitting dipole has its axis inclined at $11.5^\circ$ to the earth’s rotation axis, and its centre is displaced about 400km away from the geometric centre of the earth towards the south-western pacific, the displacement reflecting the symmetry of the magnetic field on the earth’s surface as illustrated in Figure provided. The dipole moment is approximated as $7.94 \times 10^{22}$ Am$^2$ (Petrova, 1980).

There are areas over the earth’s surface where the actual field deviates from the dipolar one. Three of the areas are located in the northern hemisphere and three others in the southern hemisphere. These areas are about the same size as the continents and have been called continental or world anomalies. The geomagnetic field undergoes slow changes in intensity and direction with periods from 20 up to 8,000 years called the secular variation. There also exists a westward drift of the magnetic field, to the first approximation contours of the continental anomalies and the phase of the secular variation are drifting westward at a rate of 0.2/yr. (Petrova, 1980).

The origin of the main field and its secular variation is commonly believed to be the liquid outer core, which cools at the outside as a result of which the material becomes denser and sinks towards the inside of the outer core and new warm liquid matter rises to the outside, thus, convection currents are generated by liquid metallic matter which move through a weak cosmic magnetic field which subsequently generates induction currents. It is this induction current that generate the earth’s magnetic field (Nettleton, 1976).
By slow convective movements, electric currents are produced in the core; these maintain the magnetic field, as in a self-exciting dynamo. Diurnal variations are small but more rigid oscillations in the earth’s field with a periodicity of about a day and amplitude averaging 25nT (Dobrin, 1974). The first variations of magnetic field that takes place within the course of the day are connected with phenomena occurring on the sun.

These variations are influenced by conditions in the atmosphere. The highly ionized layer of upper atmosphere above 80km altitude which in turn is affected by the solar emissions. Normally, steady ring currents are present in the ionosphere. In addition the outer layers of the sun corona erupt occasionally emitting corpuscular rays consisting of protons and electrons. When the corpuscles impinge upon the ionosphere, the ring currents are greatly disturbed and this affects the magnetic field of the earth (Fukushima and Kaminde, 1973).

Figure 3.1: a, b, and c vector diagram representing the Earth’s magnetic field (Keary and Brooks, 1984).
The magnetic anomaly consists of that part of the magnetic field which is caused by irregularities in the distribution of magnetized material in the outer crust of the earth. The magnetized rock produces a magnetic field around itself. If the rock is close enough to the earth’s surface, its magnetic field will combine with the earth’s field. The field from the rock constitutes the anomalous field and because fields are vectors, the combined field may be greater or smaller than the geomagnetic field acting alone. If the field from the magnetized body lies more or less in the same direction as the earth's magnetic field at the site, the two fields will reinforce each other, and the total field will be greater than the earth’s field alone and the resulting anomaly is a positive anomaly. If the two fields are opposite in direction, they will cancel each other and the total field will be smaller than the earth’s field alone, the resulting anomaly being negative (Keary and Brooks 1984).

A magnetic anomaly is detected when the measured magnetic field at the earth’s surface differs from the undisturbed geomagnetic field. This implies presence of a magnetized material below the subsurface. All magnetic anomalies caused by rocks are superimposed in the main field of the earth. A magnetic anomaly is now superimposed on the earth’s field causing a change $\Delta B$ in the total field vector $B$. Let the anomaly produce a vertical component $\Delta Z$ and a horizontal component $\Delta H$ at an angle $\alpha$ to $H$ as shown in Figure 3.1(b). Only that part of $\Delta H$ which is in the direction of $H$, namely $\Delta H'$, will contribute to the anomaly (Keary and Brooks, 1984).

\[ \Delta H' = \Delta H \cos \alpha \]  \hspace{1cm} (3.4)

Also,

\[ (B + \Delta B)^2 = (H + \Delta H')^2 + (Z + \Delta Z)^2 \]  \hspace{1cm} (3.5)
Expansion of the above equation ignoring the negligible terms in $\Delta^2$ yields,

$$\Delta B = \Delta Z \left( \frac{Z}{B} \right) + \Delta H' \left( \frac{H}{B} \right)$$  \hspace{1cm} (3.6)

Substituting the above equation with angular descriptions of geomagnetic element ratios yields,

$$\Delta B = \Delta Z \sin I + \Delta H \cos \alpha$$  \hspace{1cm} (3.7)

The above approach can be used in calculating the magnetic anomaly caused by a small magnetic pole of strength $m$, defined as the effect of this pole on a unit positive pole at the observation point.

The pole is situated at depth $z$, a horizontal distance $x$ and radial distance $r$ from the observation point and $\theta$ is the angle between a line joining the pole to the observation point to the horizontal. The force of repulsion $\Delta Br$ on the unit positive pole in the direction $r$ is given by,

$$F = \mu_0 m_1 m_2 / 4\mu_r r^2$$  \hspace{1cm} (3.8)

Where $1 m$ and $2 m$ are magnetic poles of strengths $m_1$ and $m_2$ separated by a distance $r$ and $\mu_0$ and $\mu_R$ are constants corresponding to the magnetic permeability of vacuum and relative permeability of medium separating the poles. The SI unit for $\mu_0$ is Hm$^{-1}$ and $\mu_R$ is dimensionless (Dentith, 1994).

### 3.2.1 Geomagnetic field elements

The geomagnetic field, like any magnetic field is a vector field. At any point on the Earth’s surface it is represented by a vector pointing in the direction of force on a positive pole, and having a length proportional to the strength of the field at that point. Its components are called magnetic elements. Among the magnetic elements, the direction of the field is the element least sensitive to changes in the dimensions and the magnetic properties of the subsurface body. The various magnetic elements are $B_Z$, $B_H$, $B_T$, $D$ and $I$ which describe the Earth’s magnetic field.
These elements are represented in the parallelepiped. The angle between the magnetic and the geographic meridians is the magnetic declination $D$ while that between the total geomagnetic field vector and the horizontal plane is the magnetic inclination $I$. These geomagnetic elements vary all over the Earth’s surface. The line where inclination $I$ is zero is the magnetic equator and points where the inclination is +90 and -90 are the North and South magnetic poles respectively (Wasilewski, 1973). The total field vector $B_T$ has a vertical component $B_Z$ and a horizontal component $B_H$ in the direction of the magnetic north. The vertical component $Z$ is positive north of the magnetic equator and negative south of it. The dip of $B_T$ is the inclination $I$ of the field. $B_T$ varies in strength from about 25000nT in equatorial regions to about 70000nT at the magnetic poles (Parasnis, 1986).

### 3.2.2 Rock magnetism

All rocks become magnetized because they contain magnetic minerals. Such minerals are magnetite, hematite, pyrrhotite, ilmenite, maghematite and leucoxenes but magnetite is far the most common of these minerals. Therefore for most practical purposes, rocks are said to be magnetic if they contain magnetite and their magnetic properties depend on the amount of magnetite disseminated among the non-magnetic minerals making up the principal material of the rock. Magnetite is a representative of the cubic minerals with spontaneous magnetizations comparable to the familiar ferromagnetic metals (Fe, Co, Ni). Hematite is representative of the more weakly magnetic, uniaxial minerals, in which the oppositely magnetized sub-lattices of interacting Fe$^{3+}$ ions are equally balanced, that is, anti-ferromagnetic but centered at a small angle to give slight spontaneous magnetisation perpendicular to the ion moments (Table 3.1).
The magnetism of a rock may either be induced by the earth’s field or remanent which may have occurred during cooling or deposition in the rock’s history.

**Table 3.1: Basic patterns of alignment of atomic magnetic moments by mutual interaction**

<table>
<thead>
<tr>
<th>TYPE</th>
<th>EXAMPLE</th>
<th>IONIC MOMENTS</th>
<th>NET SPONTANEOUS MAGNETISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromagnetic</td>
<td>Fe, Co, Ni</td>
<td>↑ ↑ ↑ ↑</td>
<td>↑</td>
</tr>
<tr>
<td>Antiferromagnetic</td>
<td>Ni, MnO</td>
<td>↑ ↓ ↑ ↓</td>
<td>Zero</td>
</tr>
<tr>
<td>Ferrimagnetic</td>
<td>Magnetite</td>
<td>↑ ↓ ↑ ↓</td>
<td>↑</td>
</tr>
<tr>
<td>Canted Antiferromagnetic</td>
<td>Hematite</td>
<td>↗ ↘ ↗ ↘</td>
<td>→</td>
</tr>
</tbody>
</table>

Induced magnetisation refers to the action of the field on the material where the ambient field of the earth is enhanced and the material itself acts as a magnet. This magnetisation is directly proportional to the intensity of the ambient field.

\[ I_i = kF^{3.9} \]

Where \( k \) is the volume magnetic susceptibility, \( F \) the ambient field intensity and \( I_i \) is the induced magnetisation per unit volume. The magnetic susceptibility of a rock containing magnetite is simply related to the amount of magnetite it contains. The remanent magnetization \( I_r \) is a permanent magnetisation often predominant in many igneous rocks. This magnetization depends upon thermal, mechanical and magnetic history of the material and is independent of the field in which it is measured. The remanent magnetization of a rock may not be in the same direction as the present earth’s field for the field is known to have changed its orientation in geologic time (Reeves, 1989).
3.3 Ground Magnetic method

Ground magnetic method requires acquisition of measurements of the amplitude of the magnetic field at discrete points along survey lines, distributed regularly throughout the area of interest (Telford et al., 1990). The measured magnetic field is the vector sum of; the Earth’s main field, an induced field caused by magnetic induction in magnetically susceptible earth materials polarized by the main field, a field caused by remanent magnetism of the earth material and the other fields less significant caused by solar, atmospheric and cultural influences (Telford et al., 1976). It is the induced and remanent fields that are of particular interest to geoscientists because the magnitude of these fields is directly related to the magnetic susceptibility, spatial distribution and concentration of the local crustal materials. Once the main field and minor sources are removed from the observed magnetic field data via data reduction and processing methods, the data are enhanced and presented in readiness for analysis (Milligan and Gunn, 1997). The analysis ultimately leads to an interpretation of structure, lithology, alteration and sedimentary processes (Mackey et al., 1998).

3.4 Magnetic method in exploration.

In magnetic method we measure the magnetic field produced by the causative source which may be mineral target or the host rock, after correction for the Earth’s magnetic field. Rocks containing some magnetic minerals are magnetised by induction in the main field and thus become source of anomalous magnetic field. The intensity of magnetisation induced in a rock is $K$ times the Earth’s field, where $K$ is susceptibility of the rock (McMickan et al., 1993).
This method is suitable in prospection of magnetic minerals or magnetic rocks which are always host to the target minerals. The method is also used in exploration of geothermal resource by delineating faults and hydrothermally altered rock. The magnetisation of hydrothermally altered rocks is normally lower than that of the surrounding rock. Iron ores are usually classified as strongly and weakly magnetic. Magnetite and hematite deposits of magmatic origin or hydrothermal replacements type, contact metamorphic deposits and shale, are strongly magnetic compared to hydrothermal filtration deposits of hematite and siderite and sedimentary deposits of siderite and limonite which are weakly magnetic. Some manganese and chromium ores are also highly magnetic and amenable to detection by magnetic method (McEnroe, 1997).

Pyrrholite which is associated with other economic base metal mineralization, ilmenite and other iron-titanium minerals are indicator minerals. Mineral ores can have magnetic susceptibility higher or lower than those of the host rock (Dentith, 1994), due to this sharp magnetic contrast, ground magnetic is selected as a suitable method. For example, at Hired in Iran east, magnetic susceptibility was measured in one of the target areas and there was good correlation between gold grade and magnetic susceptibility, 200-3500 x 10^{-5} SI. Total magnetic field was from stations and contour maps and models revealed anomalies representing the magnetic responses of gold ore (Karimpour et al., 2007).
CHAPTER FOUR
MATERIALS AND METHODS

4.1 Ground magnetic survey

4.1.1 Introduction

The data acquisition technique involved measurement of the magnetic intensities at discrete positions along stations regularly distributed within the area of interest so as to cover enough segment used to determine the structure and the structural history of the study area. Chemical analysis of soil samples from the area was also undertaken to determine the levels of iron and titanium oxides. The ground magnetic study of Magaoni, covered an area of about 25 km$^2$, and consisted of 20 profiles spaced 250m apart. A total of 800 magnetic intensity stations were measured with spacing of 100m intervals along each line. Each profile had a total length of 4000m and 40 magnetic intensity stations with a bearing normal to the regional structure.

The magnetic intensity measurements were recorded using a Fluxgate magnetometer that gave the earth’s vertical magnetic intensity component. Observations were made along a series of stations with equal spacing, where the magnetic intensities and station coordinates recorded at a stationary point. Stations were established using GPS (Global Positioning System) device, to give their exact positions on the earth in terms of northing and easting coordinates. A special station known as a Base Station was also established using the same positioning device. Base station was established to monitor and remove diurnal variation, which is simply the contribution to earth’s magnetic field intensities due to solar activities.
4.2 Field Equipment

4.2.1 Global Positioning System (GPS)

The Global Positioning System (GPS) is made up of a network of 24 satellites put into orbit by the U.S Department of Defense. The GPS satellites orbit the earth twice a day and transmit information to the earth. GPS receivers take this information and use triangulation to calculate the user’s exact location. Essentially, the GPS receiver compares the time a signal was transmitted by a satellite with the time it was received. The time difference tells the GPS receiver how far away the satellite is. With distance from a few more satellites, the receiver can determine the user’s position and display it on the instruments electronic map. A GPS receiver must be locked on to the signal of at least three satellites to calculate a 2D position (latitude and longitude) and track movement. With four or more satellites in view, the receiver can determine the user’s 3D position (latitude, longitude and altitude). Once the user’s position has been determined, the GPS unit can calculate other information, such as speed, bearing, track, trip distance, distance to destination, sunrise and sunset time and more.

4.2.2 Flux Gate Magnetometer

Fluxgate magnetometer uses electromagnetic induction concepts. It consists of two permeable coils that are wound inopposite directions. The coils are driven with AC signal to saturation. A secondary coil is wound around both cores to detect changes in magnetic field. In absence of external magnetic field, signals in primary coils will cancel.
In presence of external magnetic signal, one primary coil will saturate before the other, creating an imbalance in magnetic field to be detected via EM induction in secondary coil. It has a typical accuracy of 5 to 10 nT (Force, 1991).

4.3 Field Measurements
Magnetic data measurements were taken at 800 stations, distributed equally on 20 profiles. Three readings were taken at each station and average calculated to reduce errors. A base station was carefully established and was preoccupied after every two to three hours. The reading from the base station was used to correct for diurnal variation. The raw magnetic data are shown in the appendix.

4.4 Magnetic Data Correction
The reduction of magnetic data was done to remove all causes of magnetic variation or drift from the observations other than those arising from the magnetic effects of the subsurface geology. This simply means, processing the data collected to prepare them for interpretation.

4.4.1 Diurnal Variation Correction
This is done to remove the temporal variation of the earth’s main field caused by the action of solar wind. It is achieved by subtracting the time synchronized signal, recorded at the base station, from the survey data. The procedure relies on the assumption that the temporal variation of the main field is the same at the base station and in the survey area. Diurnal variation is small and smooth and electromagnetic induction effects are minimal (Milligan, 1997).
In this study, the base station was preoccupied after every two to three hours and diurnal curve plotted for the base station data. The diurnal curves were plotted for all the eleven days of the study and the following general formula was used to do the corrections. The correction was done on every raw data from every station for each day of the survey, using equation 4.1.

\[
\text{Observed value} = \text{raw magnetic value} - \text{diurnal variation correction}
\]

4.1

Figure 4.1 Diurnal curve for day seven (19/08/2014) of the study.

Figure 4.1 Diurnal curve for day seven (19/08/2014) of the study.
4.4.2 Geomagnetic Correction

It is the removal of the strong influence of the Earth’s main field from the survey data. The most vigorous method of geomagnetic correction is the use of the IGRF i.e. International Geomagnetic Reference Field is generally used for this purpose which expresses the undisturbed geomagnetic field in terms of large number of harmonized and includes temporal terms to correct for secular variation. This is done because the main field is dominantly influenced by dynamo action in the core not related to the geology of the upper crust (Lewis, 2000). This is achieved by subtracting a model of the main field from the survey data. In this survey, the IGRF values were obtained from an online calculator, based on dates, elevation and geographical location of the station or survey area. The IGRF values were subtracted from the measured data for all the stations. The anomaly obtained was used to plot a magnetic contour map and profiles of the survey area using Golden Surfer8 software.

4.5 Data Enhancement

The magnetic data collected in the study area was processed so as to prepare the dataset for interpretations. Enhancement simplifies the anomalies, making features of particular interest more prominent at the expense of others and makes attempt to relate the measured field to the property being investigated.

4.5.1 Trend Analysis

This is the removal of the influence of magnetic field of deep seated structures (regional) which are not of interest to the survey, so as to remain with the anomaly of interest (residual). Trend
analysis or regional removal was done to the data of this survey, since the ilmenite being investigated is a shallow mineral. The following equations were used for trend analysis of the 7 profiles, AA’, BB’, CC’, DD’, EE’, FF’ and GG’ respectively;

\begin{align*}
Y &= 0.00334X + 650 \\
Y &= 0.004X + 627.2134 \\
Y &= -0.0181X + 656.2134 \\
Y &= 0.0364X + 540.0974 \\
Y &= -0.035X + 614.1949 \\
Y &= -0.0483X + 646.0034 \\
Y &= -0.0035X + 618.1346
\end{align*}

4.2
4.3
4.4
4.5
4.6
4.7
4.8

X is the station position and Y is the regional field. Regional field is then subtracted from the corrected that at every X position along a profile. This was done to all the seven profiles.

The following formula was used to obtain the residual. Residual is the magnetic field of the shallow structures, which were of interest in this survey.

\[
\text{Residual field} = \text{corrected data} - \text{Regional field}
\]

4.9

Figure 4.2a shows a shift from zero, along the vertical axis. This is an indication of the presence of regional in the data along profile AA’. Figure 4.2b displays the data along the same profile after the removal of regional using equation 4.9.
Figure 4.2a A graph of profile AA’ with regional

Figure 4.2b. A graph of profile AA’ without regional
4.5.2 Reduction to the pole

This involves transforming the data to that which would be measured at the earth’s magnetic poles. This simplifies the anomalies by centring anomalies over the causative magnetic body rather than being skewed and offset to one side. In this survey, data was reduced to the pole using Euler software.

4.5.3 Vertical and Horizontal derivatives.

This enhancement quantifies the spatial rate of change of the magnetic field in vertical and horizontal directions of the profile. Derivatives essentially enhance high frequency anomalies relative to low frequencies. Euler software was used to do derivatives of the data in this study.

4.5.4 Euler deconvolution

Euler deconvolution is an imaging technique for estimating location and depth to magnetic anomaly source. It relates the magnetic field and its gradient components to the location of the anomaly source with the degree of homogeneity expressed as a structural index and it is a suitable method for delineating anomalies caused by isolated and multiple sources (El Dawi et al., 2004). Euler deconvolution is expressed in Equation as:

\[
(x - x_0) \frac{\delta T}{\delta \xi} + (y - y_0) \frac{\delta T}{\delta \eta} + (z - z_0) \frac{\delta T}{\delta \zeta} = n(B - T) \quad 4.9a
\]

Applying the Euler’s expression to profile or line-oriented data (2D source), x-coordinate is a measure of the distance along the profile and y-coordinate is set to zero along the entire profile. Equation 4.6 is then written in form of Equation as:

\[
(x - x_0) \frac{\delta T}{\delta \xi} + (z - z_0) \frac{\delta T}{\delta \zeta} = n(B - T) \quad 4.9b
\]
Where \((x_0, z_0)\) is the position of a 2D magnetic source whose total field \(T\) is detected at \((x, z)\).

The total field has a regional value of \(B\), and \(n\) is a measure of fall-off rate of the magnetic field. \(n\) is directly related to the source slope and is referred to as the structural index and depends on the geometry of the source (El Dawi et al., 2004). Estimating depth to magnetic anomaly using Euler deconvolution involves: Reduction to the pole, which means transforming the data to that which would be measured at the magnetic poles of the earth. This simplifies the anomalies by centering anomalies over the causative magnetic body rather than being skewed and offset to one side. And calculation of horizontal and vertical gradients of magnetic field data, which quantifies the spatial rate of change of the magnetic field in vertical and horizontal directions. Derivatives, essentially enhances high frequency anomalies relative to low frequencies.

### 4.6 Chemical analysis of samples

Five stations from the study area were selected randomly and soil samples collected from various depths, ranging from surface to about 50cm depth. The soil samples were collected in transparent plastic bags and labelled by pens with non-metallic ink to avoid contamination. The samples were taken to the geology laboratory in to analyse for iron and titanium oxide. Energy Dispersive X-ray Fluorescence Spectrometry (EDXS), was used for the analysis of the two minerals oxide.

#### 4.6.1 Titanium

It is one of the lightest members of the first row transition series of elements, and belongs to group four of the periodic table. It is a common lithophile metallic element that forms several minerals, including ilmenite, rutile, brookite, anatase among others. It exists as titanium dioxide \((\text{TiO}_2)\) and has a crustal abundance of 6320 mg kg\(^{-1}\) (Fyfe, 1999). The global average for the soil has been estimated as 0.33 % Ti, it has lower values for podzols and histosols. The conversion
factor of Ti to TiO$_2$ is 1.668. The median TiO$_2$ is 0.57 % in both subsoil and top soil, with a range varying from 0.012 to 3.14 % in subsoil and 0.021 to 5.45 % in top soil. These values are lower in alluvial areas for both top and subsoil (Kabata-Pendias, 2001).

The median TiO$_2$ content in stream sediments is 0.62 % with a range from 0.016 to 4.99 %. High values in stream sediment (> 0.82 %) are located mainly in areas with outcropping Palaeozoic and crystalline basement rocks of intermediate to mafic signatures (Mielke, 1979). In floodplain sediments, the values of TiO$_2$ vary from 0.05 to 2.15 % with a median of 0.48 %. High values are found in areas with mafic and ultra-mafic crystalline rocks. In floodplain sediment, TiO$_2$ shows very strong positive correlation with Nb, V, Fe$_2$O$_3$, Co and Al$_2$O$_3$ (Fyfe, 1999).

4.6.2 Iron (III) Oxide

Iron (III) oxide or Ferric oxide is an inorganic compound with formula Fe$_2$O$_3$. It is one of the main oxides of iron, the other two being Iron (II) oxide (FeO) which is rare and Iron (II,III) oxide which also occurs naturally as mineral magnetite (Fe$_3$O$_4$). As the mineral known as hematite, Fe$_2$O$_3$, is the main source of iron for the steel industry. Hematite is weakly magnetic and normally combine with titanium dioxide to form ilmenite, this explains why ilmenite is weakly magnetic (Morris, 1980).

4.6.3 Energy Dispersive X – Ray Fluorescence Spectroscopy

Spectroscopy is the study of the interaction between matter and radiated energy. Spectroscopy data is often represented by a spectrum, a plot of the response of interest as a function of wavelength or frequency. Spectral measurement devices are spectrometer. Spectroscopy is used in physical and analytical chemistry because atoms and molecules have unique spectra. As a
result, these spectra can be used to detect, identify and quantify information about the atoms and molecules. One of the central concepts in spectroscopy is a resonance and its corresponding resonant frequency. A plot of amplitude against excitation energy will have a peak centred at the resonance frequency. This plot is one type of spectrum with the peak often referred to as spectral line and most spectral lines have a similar appearance. In many applications, spectrum is determined by measuring changes in the intensity or frequency of this energy (Korkish, 1989).

Spectroscopy can be distinguished by nature of the interaction between energy and the material. It involves absorption and emission of energy by atoms after being irradiated. These absorptions and emissions are due to electronic transitions of outer shell electrons as they rise and fall from one electron orbit to another. Atoms also have distinct x-ray spectral that are attributable to the excitation of inner shell electrons to excited state. Atoms of different elements have distinct spectra and therefore atomic spectroscopy allows for the identification and quantification of a sample’s elemental composition. In this study, X-ray spectroscopy was used to test for titanium and iron oxides. The equipment used is known as EDX machine. EDX systems are attachments to Electron Microscopy instruments or Transmission Electron Microscopy instruments where the imaging capability of the microscope identifies the specimen of interest (Fyfe, 1999).

The data generated by EDX analysis consist of spectra showing peaks corresponding to the elements making up the true composition of the sample being analyzed. In this study, Energy Dispersive X-ray Fluorescence spectrometer was used to analyze for titanium and iron oxides. When the sample is irradiated with X-rays from an X-ray tube, the atoms in the sample generate
unique X-rays that are emitted from the samples. Such X-rays are known as “fluorescent X-rays” and they have unique wavelength and energy that is characteristic of each element that generates them. Consequently, qualitative analysis can be performed by investigating the wavelength of the X-ray. As the fluorescent X-ray intensity is a function of the concentration, quantitative analysis is also done by measuring the amount of X-rays at the wavelength specific to each element (Fyfe, 1999).
RESULTS AND DISCUSSION

5.1 Introduction

Interpretation of magnetic data can be done either qualitatively or quantitatively. In this research work both methods were applied. The qualitative part is largely visual inspection of magnetic map. The resultant preliminary structural element map is the cornerstone of the interpretation. Qualitative interpretation involved recognition of the nature of discrete anomalous bodies including faults and ventricular intra-sedimentary bodies and deposited features among others. The most important element in this preliminary qualitative stage was not the interpretation of anomalous bodies themselves but rather the network of shallow magnetic signatures and discrete anomalies that at first sight may appear as a pattern of unrevealed anomalies.

In quantitative interpretation, due to the inherent ambiguity in the interpretation of potential field data, it is not always advisable to go straightforward into solutions interpretation without having a rough idea about the causative bodies. First of all, the geology of the area was considered, including a study of all available information on the range of values of the intensity and inclination of the magnetization of the local rocks, and their distribution. Quantitative interpretation involves making inferences on the location, depth and shape of the anomaly causative body. In this study, Euler deconvolution technique was used for quantitative interpretation.

5.2 Interpretation of Magaoni magnetic intensity maps
The magnetic intensity colour map shows that the entire study area has weak magnetisation spread out (Figure 5.1). This indicates that the area is covered by sedimentary deposits of magnetically weak minerals or materials. The map also shows that the magnetic materials or minerals covering the area are shallow.

Figure 5.1 Magnetic intensity colour map for Magaoni.
Contour map just like the intensity colour map, shows that the whole area has weak and shallow magnetisation. The magnetic signatures are more pronounced in NE, SE, NW and SW of the area. The magnetisation of the area trends in the N-S direction, as shown in figure 5.2.

Figure 5.2 Magnetic Anomaly contour map for Magaoni.

The 3D anomaly map shows the distribution of magnetic signatures of the area, it gives the location and quantity of magnetisation in the area, (Figure 5.3). The broad and low amplitude shown by the colours, represent shallow and weak magnetisation of the area. The three points where there is sharp and high amplitude of the colours, indicate buried strong magnetic materials such as metal pipes, metal drums or tarmac road.
Qualitative interpretation of the magnetic field intensity shows higher magnetic values to the north-east direction running through to the south-west (640nT). The probable cause of this high magnetic signature could be due to the presence of iron ores which have high magnetic susceptibility. This is in agreement with the geologic description of the orientation of ferrous deposits in Kwale region. The location of ilmenite deposit is characterized by very low and shallow magnetic anomaly as revealed in the map. The deposits on the northern part of the region and that on the southern part lie on the relatively low magnetic intensity regions, that is,
530nT and 550nT respectively. In the NW and SW orientation are regions of low magnetic intensities indicating the presence of magnetically weak minerals such as ilmenite deposits with the same orientation. Thus, low magnetic intensities in the NW and SW orientation as evidenced in the anomaly map are due to weak magnetic minerals to non-magnetic minerals as a result of presence of small quantity of iron.

5.3 Interpretation of magnetic data along the profiles

Figure 5.4 shows Euler solutions for magnetic anomaly along profile AA’. Here, three distinct trends are evident which coincide with the location of ilmenite deposits within the study area. The profile begins with a relatively low magnetic anomaly points which could be the mineral sand layer. The next zone (550m-650m) shows no magnetic sources. The lack of magnetic sources exists mostly between the faults or underground pits. These signatures are followed to the south by relatively high signatures (600m-1000m and 2000m - 2500m) along the profile and are postulated to be magnetic mineral. The entire profile is characterized by small amplitude curves of the anomalies, which shows that shallow source anomalies are present.
Figure 5.4: *Euler depth solution along magnetic anomaly profile AA’*

Figure 5.5 shows high magnetic signatures at a depth of about 90m below the surface for profile BB’ at 100m-300m along the profile and these are associated with iron or other magnetic bodies. Horizontal and vertical gradients highly fluctuate over a distance 800m (0m-800m) along the profile. This represents abrupt lateral change in magnetization. The sharp and high amplitude of the anomalies between 400m and 450m, strong and shallow magnetisation which could be ilmenite.
In profile CC’ as shown in figure 5.6, there is concentration of Euler solutions between 1600m and 1800 along the profile an indication of a strong and shallow magnetic source body at a depth ranging from the surface to about 70m. The profile shows discontinuities between 100m-900m and 1100m- 1500m, an indication of a fault or underground pits. The largest part of the profile showed lack of magnetisation.
5.6: Euler depth solution along magnetic anomaly profile CC’

Figure 5.7 shows three distinct anomalies along profile DD’. There exist high magnetic sources around (0m - 100m), (800m - 1200m) and (1500m-2400m) which is an indication of highly magnetic materials near the surface. The shoulder of the reduction to the pole (RTP) outlines the edge of a possible magnetic structure located at profile distance.
Figure 5.8 shows profile EE’. There is an abrupt change in magnetisation between 900m and 1600m along the profile. This represents the existence of a magnetically strong source lying between 0m-300m depth, and a very low magnetic signature between 0m – 900m along the profile which could be an indication of a buried pit zone. The discontinuity shown by the solution between 300m and 700m could be a fault.

Figure 5.8: Euler depth solution along magnetic anomaly profile EE’

Figure 5.9 shows Euler solution for profile FF’. Horizontal and vertical gradients highly fluctuate over the entire profile, this indicates change in magnetisation over distance. Sharp and high amplitudes of the anomalies at 1000m and 1500m along the profile, clearly indicate shallow magnetic structures. Cluster is observed along the entire profile, this shows the presence of magnetic structures on the profile at a depth of between 0m and 300m.
It is evident in figure 5.10 that Euler solution for profile GG’ shows magnetisation at a depth of about 450m from 0m to 500m along the profile. Between 500m and 1000m, there is a discontinuity which could possibly be a buried it or fault. There is clustering between 1000m and 2500m, indicating presence of shallow magnetic bodies around that region. There is an abrupt change in both horizontal and vertical gradient between 2250m and 2750m, this shows there exists a body strong magnetisation around that area.
These undulating signatures and the Euler deconvolution solutions clearly show shallower subsurface magnetic deposits within the geological area.

5.4 Interpretation of the chemical analysis result.

Sample SS13 was obtained from the surface at station N9516376, E0551360, SS16 was obtained from a depth of 0.5m at N9519776, E0551610, SS20 from a depth of about 1m at N9518276, E0553610, SS21 was taken from the surface at N9516476, E0555860 and sample SS24 was taken from a depth of about 0.7m at N9520176, E0555110. Table 5.1 shows the quantitative analysis results from EDX Fluorescence Spectroscopy of the soil sample SS13. The result gives the highest percentage for silicate (SiO$_2$ 92 %), this was expected because the area is full sand deposit which is normally the carrier of the mineral under investigation. Titanium dioxide (TiO$_2$)
was found to be 4.4 %, this is way above the global average of TiO₂ in the soil which is approximately 0.7 %. Iron III Oxide (Fe₂O₃) was in small quantity, about 1.7 %. Considering the percentage oxides of iron and titanium, it shows the likelihood of the existence of leucoxene, which is altered ilmenite arising due to the leaching of iron.

Results for sample SS16 shows greatest percentage of silicate due to the abundance of sand in the area (SiO₂ 79.9 %), as shown in table 5.2. From the same sample, we see an elevated value of titanium dioxide (TiO₂ 13 %), it is so much above the average value for sedimentary deposit. Comparing the percentage of titanium dioxide and that of Fe₂O₃ which is approximately 4 %, it clearly indicates the presence of ilmenite or leucoxene. Table 5.3 shows analysis result for SS20 showing high values for SiO₂ 82.87 % and Al₂O₃ 10.24 %, this may represent the availability of bauxite in the area. The percentage values for titanium dioxide which was 2.898 % and that of iron (iii) oxide about 2.151 % shows the presence of heavy minerals could be ilmenite since the difference in the percentage oxide for iron and titanium is not that much.

Sample SS21 also had a high value of silicate (SiO₂ 90.955 %), evident in table 5.4, showing abundance of sand in the study of area. There is an elevated value for titanium dioxide (TiO₂ 4.575 %) and a lower value for iron oxide (Fe₂O₃ 1.554 %), this is evident that ilmenite or ilmenite in form of leucoxene exists in the sample. The result for SS24 shows high values for silicate and bauxite. Iron and titanium oxides have 3.678 % and 3.178 % respectively, as shown in table 5.5, these values correlate well with the existence of ilmenite. All the three samples gave results showing the percentage of titanium dioxide being above the global average and again
comparing with the values for iron oxide, they indicate the presence of ilmenite and leucoxene. The samples also showed presence of zircon which is a heavy mineral sand and normally occurs with rutile and ilmenite.

Table 5.1 Analysis result for sample SS13

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Result</th>
<th>(Std.Dev.)</th>
<th>Proc.-Calc. Line</th>
<th>Int.(cps/uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>92.146 %</td>
<td>(0.920) Quan-FP</td>
<td>SiKa</td>
<td>0.4307</td>
</tr>
<tr>
<td>TiO2</td>
<td>4.411 %</td>
<td>(0.106) Quan-FP</td>
<td>TiKa</td>
<td>2.9330</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>1.740 %</td>
<td>(0.032) Quan-FP</td>
<td>FeKa</td>
<td>4.6302</td>
</tr>
<tr>
<td>SO3</td>
<td>1.255 %</td>
<td>(0.077) Quan-FP</td>
<td>S Ka</td>
<td>0.0295</td>
</tr>
<tr>
<td>ZrO2</td>
<td>0.448 %</td>
<td>(0.005) Quan-FP</td>
<td>ZrKa</td>
<td>13.4179</td>
</tr>
</tbody>
</table>
### Table 5.2 Analysis result for sample SS16

<table>
<thead>
<tr>
<th>Analyte</th>
<th>TG kV</th>
<th>uA</th>
<th>FI</th>
<th>Acq. (keV)</th>
<th>Anal. (keV)</th>
<th>Time (sec)</th>
<th>DT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-U</td>
<td>Rh 50</td>
<td>14-Auto</td>
<td>0-40</td>
<td>0.00-40.00</td>
<td>Live-</td>
<td>49</td>
<td>26</td>
</tr>
<tr>
<td>Na-Sc</td>
<td>Rh 15</td>
<td>446-Auto</td>
<td>0-20</td>
<td>0.00-4.40</td>
<td>Live-</td>
<td>50</td>
<td>26</td>
</tr>
</tbody>
</table>

#### Quantitative Result

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Result</th>
<th>(Std. Dev.)</th>
<th>Proc.-Calc. Line</th>
<th>Int. (cps/uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>79.852%</td>
<td>(0.610) Quan-FP</td>
<td>SiKα</td>
<td>0.7875</td>
</tr>
<tr>
<td>TiO2</td>
<td>13.357%</td>
<td>(0.113) Quan-FP</td>
<td>TiKα</td>
<td>19.8165</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>4.338%</td>
<td>(0.037) Quan-FP</td>
<td>FeKα</td>
<td>20.9211</td>
</tr>
<tr>
<td>ZrO2</td>
<td>1.712%</td>
<td>(0.008) Quan-FP</td>
<td>ZrKα</td>
<td>80.6791</td>
</tr>
<tr>
<td>SO3</td>
<td>0.648%</td>
<td>(0.045) Quan-FP</td>
<td>S Kα</td>
<td>0.0354</td>
</tr>
<tr>
<td>MoO3</td>
<td>0.093%</td>
<td>(0.004) Quan-FP</td>
<td>MoKα</td>
<td>4.3596</td>
</tr>
</tbody>
</table>

### Table 5.3 Analysis result for sample SS20

<table>
<thead>
<tr>
<th>Analyte</th>
<th>TG kV</th>
<th>uA</th>
<th>FI</th>
<th>Acq. (keV)</th>
<th>Anal. (keV)</th>
<th>Time (sec)</th>
<th>DT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-U</td>
<td>Rh 50</td>
<td>14-Auto</td>
<td>0-40</td>
<td>0.00-40.00</td>
<td>Live-</td>
<td>50</td>
<td>24</td>
</tr>
<tr>
<td>Na-Sc</td>
<td>Rh 15</td>
<td>506-Auto</td>
<td>0-20</td>
<td>0.00-4.40</td>
<td>Live-</td>
<td>50</td>
<td>24</td>
</tr>
</tbody>
</table>

#### Quantitative Result

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Result</th>
<th>(Std. Dev.)</th>
<th>Proc.-Calc. Line</th>
<th>Int. (cps/uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>82.871%</td>
<td>(0.582) Quan-FP</td>
<td>SiKα</td>
<td>0.8236</td>
</tr>
<tr>
<td>Al2O3</td>
<td>10.247%</td>
<td>(0.575) Quan-FP</td>
<td>AlKα</td>
<td>0.0234</td>
</tr>
<tr>
<td>TiO2</td>
<td>2.898%</td>
<td>(0.054) Quan-FP</td>
<td>TiKα</td>
<td>4.7155</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>2.151%</td>
<td>(0.022) Quan-FP</td>
<td>FeKα</td>
<td>14.3774</td>
</tr>
<tr>
<td>SO3</td>
<td>1.253%</td>
<td>(0.047) Quan-FP</td>
<td>S Kα</td>
<td>0.0713</td>
</tr>
<tr>
<td>ZrO2</td>
<td>0.329%</td>
<td>(0.003) Quan-FP</td>
<td>ZrKα</td>
<td>24.3511</td>
</tr>
<tr>
<td>MnO</td>
<td>0.186%</td>
<td>(0.010) Quan-FP</td>
<td>MnKα</td>
<td>1.0144</td>
</tr>
<tr>
<td>V2O5</td>
<td>0.065%</td>
<td>(0.023) Quan-FP</td>
<td>V Kα</td>
<td>0.1462</td>
</tr>
</tbody>
</table>
### Table 5.4 Analysis result for sample SS21

<table>
<thead>
<tr>
<th>Measurement Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument: 800HS2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analyte</th>
<th>TG</th>
<th>kV</th>
<th>uA</th>
<th>FI</th>
<th>Acq.(keV)</th>
<th>Anal.(keV)</th>
<th>Time(sec)</th>
<th>DT(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-U</td>
<td>Rh</td>
<td>50</td>
<td>14-Auto</td>
<td>---</td>
<td>0 - 40</td>
<td>0.00-40.00</td>
<td>Live-</td>
<td>49</td>
</tr>
<tr>
<td>Na-Sc</td>
<td>Rh</td>
<td>15</td>
<td>598-Auto</td>
<td>---</td>
<td>0 - 20</td>
<td>0.00-4.40</td>
<td>Live-</td>
<td>50</td>
</tr>
</tbody>
</table>

**Quantitative Result**

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Result</th>
<th>(Std.Dev.)</th>
<th>Proc.-Calc.</th>
<th>Line</th>
<th>Int.(cps/uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>90.955 %</td>
<td>(0.552) Quan-PP</td>
<td>SiKa</td>
<td>0.9214</td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>4.575 %</td>
<td>(0.075) Quan-PP</td>
<td>TiKa</td>
<td>6.6241</td>
<td></td>
</tr>
<tr>
<td>Fe2O3</td>
<td>1.554 %</td>
<td>(0.021) Quan-PP</td>
<td>FeKa</td>
<td>8.6307</td>
<td></td>
</tr>
<tr>
<td>ZrO2</td>
<td>0.860 %</td>
<td>(0.140) Quan-PP</td>
<td>BaLa</td>
<td>0.6571</td>
<td></td>
</tr>
<tr>
<td>ZrO2</td>
<td>0.813 %</td>
<td>(0.005) Quan-PP</td>
<td>ZrKa</td>
<td>49.9294</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.5 Analysis result for sample SS24

<table>
<thead>
<tr>
<th>Measurement Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument: 800HS2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analyte</th>
<th>TG</th>
<th>kV</th>
<th>uA</th>
<th>FI</th>
<th>Acq.(keV)</th>
<th>Anal.(keV)</th>
<th>Time(sec)</th>
<th>DT(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-U</td>
<td>Rh</td>
<td>50</td>
<td>15-Auto</td>
<td>---</td>
<td>0 - 40</td>
<td>0.00-40.00</td>
<td>Live-</td>
<td>49</td>
</tr>
<tr>
<td>Na-Sc</td>
<td>Rh</td>
<td>15</td>
<td>446-Auto</td>
<td>---</td>
<td>0 - 20</td>
<td>0.00-4.40</td>
<td>Live-</td>
<td>50</td>
</tr>
</tbody>
</table>

**Quantitative Result**

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Result</th>
<th>(Std.Dev.)</th>
<th>Proc.-Calc.</th>
<th>Line</th>
<th>Int.(cps/uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>77.865 %</td>
<td>(0.616) Quan-PP</td>
<td>SiKa</td>
<td>0.7316</td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td>13.637 %</td>
<td>(0.645) Quan-PP</td>
<td>AlKa</td>
<td>0.0303</td>
<td></td>
</tr>
<tr>
<td>Fe2O3</td>
<td>3.678 %</td>
<td>(0.028) Quan-PP</td>
<td>FeKa</td>
<td>24.0922</td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>3.178 %</td>
<td>(0.054) Quan-PP</td>
<td>TiKa</td>
<td>5.2090</td>
<td></td>
</tr>
<tr>
<td>ZrO2</td>
<td>1.065 %</td>
<td>(0.048) Quan-PP</td>
<td>S Ka</td>
<td>0.0608</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.315 %</td>
<td>(0.003) Quan-PP</td>
<td>ZrKa</td>
<td>21.4556</td>
<td></td>
</tr>
<tr>
<td>V2O5</td>
<td>0.188 %</td>
<td>(0.010) Quan-PP</td>
<td>MnKa</td>
<td>1.0133</td>
<td></td>
</tr>
<tr>
<td>V2O5</td>
<td>0.073 %</td>
<td>(0.022) Quan-PP</td>
<td>V Ka</td>
<td>0.1654</td>
<td></td>
</tr>
</tbody>
</table>
5.5 Discussion of magnetic data.

Magaoni lies within the Magarini sand formation which which was deposited during pliocene times and consists of unconsolidated sediments derived from the Duruma sandstone series. The magarini sands are aeolian origin deposited as coastal dunes, after erosion. Kwale deposit is associated with Heavy Minerals mainly ilmenite, rutile and zircon locally concentrated. Ilmenite is weakly magnetic, this is the reason why the entire study area exhibits low magnetic signatures apart from a few areas which could be having buried materials with strong magnetisation, for instance some points in the SE, NE and NW of the study area. The analysed magnetic results from the area show coherence with the existance of ilmenite. The results clearly portrayed low or weak magnetisation of the area, and from the geological report and previous exploration in other parts of the world it is probable that ilmenite exists dominantly in the area as sediments.

For instance, In Finland, at Loivusaarenneva and Kairineva, magnetic method was used to prospect ilmenite. The magnetic survey was conducted to measure the Total magnetic field of the survey area, the results showed weak surficial magnetization. The analysed results indicated consistence with ilmenite. Kappameter KT9 was used to measure magnetic susceptibility of samples and it showed a weak mean value of 0.002 SI, which is within the range of ilmenite (Karkkainen, 1999a).

In Lizard Complex, around Trelan and Traboe, ground magnetic method was applied in the prospection of ilmenite. The results showed weak magnetisation with sharp, high frequency anomalies of amplitudes in the range of 500nT. The susceptibilities measured were in the
average of order $10^4$SI, the results were used in the drilling and mining of ilmenite in the study areas (Leak et al., 1992).

5.6 Discussion of chemical analysis results

Chemical analysis results of samples from Magaoni gave good results, with percentage TO$_2$ ranging from 2.898 % to 13.357 %. The results are consistent with presence of ilmenite as indicated by chemical analysis results from studies carried out in certain parts of the world. For example, table 5.6 shows Chemical analysis result for soil samples studied using XRF from Ocean Drilling Program in United States of America. the percentage oxide of titanium ranged between 0.98 % to 3.17 % and iron oxide between 11.82 % and 15.65 %. The results indicated presence of ilmenite in the samples, this was realized when another study was done on the same samples to determine for ilmenite as a mineral, the results were positive especially for samples 706 and 713A, with 3.17 % and 1.52 % TO$_2$ respectively (Housden et al., 1988).

In Lizard Complex, Trelan Cornwall, chemical analysis was done on soil samples to determine the percentage of titanium oxide that would be used to infer the presence of ilmenite. The samples were taken from the surface to a depth of 2.3m. The results from borehole 1 and 2 ranged from 0.4% to 4.4% TO$_2$ while for borehole 3 and 4, the range was from 0.6% to 7.6%. These results were used to compliment magnetic survey data carried out in the same area. Lizard Complex is reach in ilmenite deposits (Leak et al., 1992).
Table 5.6 Chemical analyses result for soil samples studied using XRF from Ocean Drilling Program (Housden et al., 1988).

<table>
<thead>
<tr>
<th>Core, Section interval(cm)</th>
<th>Depth (mbsl)</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>115-706C-4R-3, 10-13</td>
<td>66.70</td>
<td>48.04</td>
<td>3.17</td>
<td>13.67</td>
<td>15.65</td>
<td>0.20</td>
<td>5.65</td>
<td>10.35</td>
<td>2.61</td>
</tr>
<tr>
<td>115-707C-25R-1,39-43</td>
<td>404.90</td>
<td>49.60</td>
<td>1.38</td>
<td>14.90</td>
<td>13.49</td>
<td>0.16</td>
<td>7.10</td>
<td>11.99</td>
<td>2.15</td>
</tr>
<tr>
<td>115-707C-25R-3,44-47</td>
<td>407.80</td>
<td>49.70</td>
<td>1.45</td>
<td>15.10</td>
<td>13.32</td>
<td>0.17</td>
<td>7.15</td>
<td>11.24</td>
<td>2.23</td>
</tr>
<tr>
<td>115-713A-15R-4,7-13</td>
<td>131.90</td>
<td>49.36</td>
<td>1.31</td>
<td>14.13</td>
<td>13.27</td>
<td>0.19</td>
<td>8.58</td>
<td>11.32</td>
<td>2.18</td>
</tr>
<tr>
<td>115-713A-15R-41,43-146</td>
<td>132.63</td>
<td>49.07</td>
<td>1.52</td>
<td>13.58</td>
<td>14.71</td>
<td>0.25</td>
<td>5.64</td>
<td>12.11</td>
<td>2.29</td>
</tr>
<tr>
<td>115-715A-25-6,38-42</td>
<td>237.00</td>
<td>47.93</td>
<td>0.98</td>
<td>14.98</td>
<td>11.82</td>
<td>0.18</td>
<td>10.97</td>
<td>11.64</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Chemical analysis results of Magaoni have shown consistence with the studies carried out in other parts of the world where ilmenite was being prospected and found. The percentage oxide especially for titanium was found to be above the global average of titanium oxide that indicates the presence of ilmenite. The chemical analysis of samples of this study area was done to support the magnetic survey findings obtained. Magnetic anomaly data and chemical analysis data concur in indicating the presence of ilmenite in Magaoni.
6.1 Introduction
The interpretation of ground magnetic data of shallow and magnetically weak minerals is usually affected negatively by the existence of high magnitude and frequency anomalies due to other shallow seated formations which are not of interest. These conceal or distort components of the anomalies due to other shallow sources, which are of more interest in mineral exploration. Anomalies due to deep seated sources do not constitute a major problem in magnetic surveys because they can be eliminated by trend analysis. The main purpose of this study was to establish ilmenite Aeolian or alluvia deposits within the study area.

6.2 Conclusions
The visual inspection and analysis of the magnetic anomaly map of the study area, Euler solutions of profiles and the quantitative results of the chemical analysis of soil samples revealed that Magaoni area as a whole is generally characterized by a broad and low magnetic signatures. Chemical analysis results showed elevated values of titanium dioxide, varying from 1.5 to 13 %, the percentages were way above the global average 0.7 %. The percentage iron oxide was low, ranging from 1.5 % to 4 %, this being the reason for weak magnetisation of the study area. The percentage oxides for iron and titanium, gave a good correlation for the existence of ilmenite. Besides, it includes surficial or local anomalies of shallow seated sedimentation, throughout the area. The average depth for the near surface magnetic anomaly is 40 m which is the depth range within which economically viable ilmenite is found, while that of the deep seated anomaly sources is about 500m. The magnetic signatures are more pronounced in the NE and SE of the area.
study area. All the above data give clear indication of the presence of mineral sand containing iron and titanium oxides, which could be simply ilmenite.

6.3 Recommendations

The ground magnetic survey and partial geochemical study carried out in Magaoni area cannot be regarded as an end but as a valuable piece of work for further research and development. Since mineral exploration requires multi-disciplinary approach, other exploration methods such as detailed geochemical, geological and other geophysical techniques need to be embraced. Consequently, aeromagnetic method can be carried out to discern deeper old dunal deposits. Ground magnetic method with smaller station spacing can be done, spacing of about 10m, since the spacing of 100m used in this research could have missed out on many subsurface deposits and structures. Therefore this study needs to be carried out using the latest technology so as to reveal the lithological structure of the area and also minimize on the errors in the survey. This will assist in delineating as many ilmenite deposits as possible and as a result, the growing global demand for ilmenite will be met. Chemical analysis should also be done extensively, for instance, more samples be collected and analyzed. Several samples to be obtained from each profile and tested using most modern techniques for the mineral itself and not oxides of constituent elements. The results of the study shows that Magaoni has ilmenite of economic value and therefore mining of the mineral can be done once a confirmation survey has been done using another geophysical technique, such as gravity technique.
REFERENCES


APPENDIX: I DIURNAL CURVES

DIURNAL CURVE(day1)

DIURNAL CURVE(day2)

Magnetic Field (nT)

Time of the day

Datum
Magnetic Field (nT) vs. Time of the day for DIURNAL CURVE (day 9 and day 10).
APPENDIX II: PROFILE GRAPHS

Graph of profile BB’ with regional

Graph of profile BB’ without regional
Graph of profile CC’ with regional

Graph of profile CC’ without regional
Graph of profile DD’ with regional

Graph of profile DD’ without regional
Graph of profile EE’ with regional

Graph of profile EE’ without regional
Graph of profile FF' with regional

Graph of profile FF' without regional
Graph of profile GG’ with regional

Graph of profile GG’ without regional
APPENDIX III: SOIL SAMPLE PLATES.

Plate 1: Sample SS13.

Plate 2: Sample SS16.
Plate 3: Sample SS20.

Plate 4: Sample SS21.
Plate 5: Sample SS24.