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# GEOPHYSICAL METHODS: ECONOMICAL TOOLS IN STRATEGIC PLANNING FOR MINING METALLIFEROUS DEPOSIT

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## ABSTRACT

Mining of mineral deposits is never properly done in isolation, nor is it an entity in itself. It is usually preceded by geologic and geophysical investigations which locate the deposits and economic analyses that prove it financially feasible. If proper investigations are not done using geophysical and geological methods, it can lead to waste of resources. Applications of geophysics in the realm of mining engineering is not a new research but it has not been discussed before has a key component of strategic planning in mine operation. Metalliferous mining industry as a whole has been slow to introduce geophysics into mines. Geophysics has the potential to reduce risks in mine development. Geophysical methods if appropriately applied, can improve performance in a number of spheres, including cost per tonne, safety, and environmental impact. This research reviewed geophysical methods as economical tools in strategic planning for mining metalliferous deposits with the intention of guiding mining companies in effective performance and maximize profit

**KEYWORDS**: Mining, geophysical methods, strategic planning, metalliferous.

## I. INTRODUCTION

Strategic planning and its execution is the key to success in mining organizations and in every establishment. Research in this area of study is therefore important for triumph of mining industries. Managers and engineers in mining industries need in-depth knowledge of mine planning to adjust to changes in random fluctuations. Many researchers have defined strategic planning in different forms. The views of researchers are different, but they have the same goal of accomplishing the predetermined objectives of the organization. The definition of strategic planning is broad and very complex. Strategy deals with very big decisions an organization has to take that ultimately determine its success or failure. Therefore, managers of organizations have to take everything regarding their business into consideration before setting their plan of action. Strategy in mining organizations is quite difficult to handle compared to other organizations because of random fluctuations.

Bain and Company(2015), defined strategic planning as a comprehensive process for determining what a business should become and how it can best achieve that goal. It appraises the full potential of a business and explicitly links the business's objectives to the actions and resources required to achieve them. Strategic planning offers a systematic process to ask and answer the most critical questions confronting a management team. Kock(2007), explained that mining strategy formulation or strategic mine planning can be viewed as the convergence of the two disciplines of business strategy and mining optimization. Strategic mine planning is concerned with the manner in which orebodies are exploited in order to compete in the marketplace. Strategic planning is an organizational management activity that is used to set priorities, focus energy and resources, strengthen operations, ascertain that employees and other stakeholders are working toward common goals, establish agreement around intended outcomes, assess and adjust the organization's direction in response to changing environment (Dinco et al., 2016).According to Golder Associates (2017), mine planning and mineral evaluation is the process of using various types of information, including geological, geotechnical, metallurgical, and other data to develop mine designs, production schedules, equipment lists, man power numbers and cost estimates to enable the technical and financial feasibility of a project to be determined. To sum it up, strategic planning is the process of thinking through the current mission of the organization and the current environmental conditions facing it, then setting forth a guide for tomorrow decisions and results. Strategy is, in short, fundamental to an organization's success, which is why the study of strategy can be both profitable and intellectually engaging (Besanko et al., 2013).

Having discussed strategic planning and role of geophysics in mine development, it is highly necessary to review existing research related to use of geophysics in metalliferous deposits. Hence, this research reviewed previous studies using available information in text books, journals, articles, and online materials available on different websites related to the subject of discussion. This work is organized into four parts. Part one presents the general introduction of strategic planning and why geophysical methods are necessary in mine planning. Second part reviews relevant literatures on geophysical methods. The third part discusses prospecting for metallic deposits using appropriate geophysical methods as tools in strategic planning. Finally, discussions and conclusions of the research was discussed in part four.

**Strategic management process**

According to Dinko et al., (2016) strategic management process has four common phases as follows:

1. Strategic analysis
2. Strategy formulation
3. Strategy implementation
4. Strategy evaluation

***Strategic analysis***

Strategic analysis is the process of gathering, examining and providing information for strategic purposes. This phase involves examining the internal and external factors affecting an organization.

***Strategy formulation***

Strategy formulation is the process of determining the best course of action for realizing organizational objectives, and hence achieving organizational purpose. Managers formulate corporate, business and functional strategies after conducting strategic analysis.

***Strategy implementation***

Strategy implementation entails designing the organization's structure, allocating resources, developing the decision-making process and human resource management.

***Strategy evaluation***

Strategy evaluation is the final phase of strategy management process. The main strategy evaluation actions are: assessing external and internal factors from which the current strategies are based, evaluating performance, and taking remedial actions. Evaluation ascertains that the organizational strategy, as well as its implementation meet the organizational objectives.

**Role of geophysics in mine development**

The role of geophysics in mineral exploration has expanded rapidly in recent decades, but in mining its importance is only just being recognized(Fallon et al, 2007).Mining of mineral deposit is never properly done in isolation, nor is it an entity in itself. It is usually preceded by geological, geophysical and geochemical investigation that determining economic viability of the deposits. If the mineral deposit is proven, then other processes of mining follows; otherwise, resources used for the investigations is wasted. If proper investigations are not done using geophysical and geological method, it can leads to waste of resources. Geophysical methods are non-destructive methods that are increasingly being used in engineering practice. Meho et al, (2013) discussed that, the use of geophysics in engineering practice in term of economic and time savings when compared to borehole investigations. Portability, high speed and low labor cost are the main advantages of the geophysical methods in comparison with the traditional geological-engineering survey methods(Pupatenko et al., 2017).

When suitable physical contrasts exist, geophysics has the potential to reduce the risks in mine development decision-making via timely and cost-effective mapping of the orebody and its environment. Geophysics, appropriately applied, can underp in mine performance improvements in a number of spheres, including cost per tonne, safety, and environmental impact(Fallon et al, 2007).Meho et al, (2013) recommended use of geophysical methods for preliminary mineral investigations in order to provide a general picture of the underground structure. A comprehensive programme of boreholes and trial pits is expensive which has resulted in increased use of geophysical methods (Culshaw et al., 2000).

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Excluding commodity price and sovereign risk, uncertainty about ore geometry and rock quality are the principal threats to mine performance. In mine development, major capital expenditures are committed on the basis of sparse information. Likewise during mining, local inaccuracies in mine models based on incomplete data sets are not infrequently the root cause of unexpected and sometimes costly production shortfalls, through lost ore or bad ground(Fullagar & Fallon, 1997). Geophysics, if appropriately applied, can underpin mine performance improvements in a number of spheres, including cost per tonne, safety, and environmental impact. Benefits arising from a geophysics implementation may be direct, in terms of immediate cost reduction, or indirect in the form of an improved ore body model, better mine design, or a timely recognition of safety hazards (Fullagar & Fallon, 1997).

According to Fullagar and Fallon, (1997) four broad classes of application of geophysical methods can be recognized as follows:

1. Ore body delineation, to maximize ore recovery and minimize dilution;
2. rock mass characterization, to guarantee safety and to optimize mine design;
3. exploration and ground sterilization, and
4. environmental monitoring.

Geophysical methods play an important role in strategy formulation. The manager needs to decide on which geophysical method is appropriate to mine mineral deposit to reduce cost of drilling. Interpretation of data acquired using geophysical techniques give a better idea of mineral concentration and required expertise to give clear information of the deposits. Hence, managers should employ geophysicists who are in charge of preliminary investigation of ore deposits in order to save cost and have reliable information.

In a recent publication by Ross and Bourke (2017), it was discussed that measurement of rocks physical properties is gaining importance in mining exploration. First, there is a growing recognition of the value of integrating physical property data and potential field surveys. This can be done through constrained geophysical inversions (Boszczuk et al., 2011), or in preparing mineral exploration maps (Hayward et al., 2013). Second, physical property data are also needed to generate predictive geophysical exploration models for specific types of ore deposits (Clark, 2014). Third, these data can be integrated with geochemical and mineralogical data to give constrains on the origin of some ore deposits (Chu et al., 2015).

## II. GEOPHYSICAL METHODS

### Introduction

Geophysical techniques can provide means for more cost-effective in ore body prospecting. This make it indispensable tools for strategic planning in mine operations. As pointed out by Fullagar and Fallon (1997),geophysical methods are already playing an important role in a number of metalliferous mines around the world, especially for oreboundary delineation, delivering benefits measured in millions of dollars per year in some cases. It was stressed that the greatest impediment to expanded use of geophysical methods at mines is low level of awareness of geophysics by mine geologists, engineers, and managers. If the level of awareness increase, it would create more technological advancement in the nearest future. The number of drill hole would be reduced drastically which leads to more profit. Mukherjee (2011) discussed that geophysical techniques are routinely used in an exploration programme to help the project geologist delineate areas favourable for the type of target being pursued. Geophysical surveys measure the variation of physical quantities, with respect to position or time. It rely on variations in the physical properties of the mineralized rocks. Measured data can be analyzed to give internal distribution of physical properties so as to reveal how surbsurfacephysical properties vary vertically and laterally. Before begins a survey, it is important to ensure that the survey grid (a *grid*is a two dimensional structure made up of series of intersecting straight line which serve as guide to locate where reading is taking) is laid out toenhance the response from the bodies of interest. Normally the grid is oriented so that the surveylines cross the strike of the expected target at right angles. If the results of an airbornegeophysical survey are available, then the grid can be oriented to cross interesting airborneanomalies at right angles(Scott, 2014).As expressed by White(2005), a major advantage of geophysical techniques is that they can detect responses from mineralization buried several hundred metres below the ground surface. The application of geophysical methods is very wide, because we can study the deepest regions of the Earth until the detection of very superficial structures. According to Teixidó(2012), geophysics has numerous applications in geology, mining, environmental sciences, geotechnical engineering, civil engineering, hydrology, archeology among others.
Fallon et al., (1997) expressed that geophysics is not a panacea at mining operations, but should be viewed as an additional source of tools to deploy in the continuous struggle to maximize overall performance. Searching for

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deep exploration targets is one of the main issues in mining industry today, as easily detectable ore bodies become rarer. Much effort has been made by researchers to discuss applications of geophysics but geophysical methods are still been underutilized.

According to Reynolds, (1997) geophysical techniques can be classified into two: passive and active techniques. In the passive category, existing force fields are measured directly without instrumentally generated signals and the results are interpreted in terms of subsurface features perturbing the field. Magnetic and gravity measurements fall in this category. In the active methods, instrumentally generated signal pass through the subsurface, detected and recorded by the instrument. Seismic techniques, electromagnetic techniques (including the use of simple metal detector, the pulsed- induction metal detector and the soil conductivity meter), earth resistivity measurements and ground-penetrating radar are all active devices.

**Magnetic method**

Magnetic method utilizes small variations in magnetic mineralogy among rocks. Magnetic susceptibility is the physical parameter measured in magnetic survey and is a measure of rocks response to a local applied magnetic field. Magnetic susceptibility is typical for precambrian, metamorphic and highly deformed terrains (Survey, 2015). The standard instrument in use remains the proton magnetometer (Figure 5)and the major improvement to the instrumentation has been the addition of microprocessor control to record the data for downloading to a computer at suitable points in the survey(Culshaw et al., 2000).Magnetic survey can be performed on land, at sea and in the air using magnetometer(Reynolds, 1997).Murphy(2014), asserted that a good knowledge of the proxy relationship between magnetic susceptibility and the mining-processing response of rock can facilitate prediction and forecasting of variability in parcels of ore in a large operation. Minerals that can cause a significant magnetic response are magnetite, pyrrhotite, hematite, ilmenite/titanohematite and maghemite (Survey, 2015).

Aeromagnetic survey is the most appropriate for regional investigation. It is cost effective and cover large are in short time. Resolution of data (data is usually presented as in Table 1 and Table 2) acquired depend on the altitude and interval between grids (Figure 1 and Figure 2 represent typical survey grids pattern for aeromagnetic and ground magnetic survey respectively). For good resolution, survey clearance must be small and grids close to each other. Camera and Guimarães (2016), discussed that magnetic method was the first geophysical airborne research method. It was discovered by Faraday, Sect. XIX, and was initially employed by the USSR (currently Russia) in 1936. Ground survey can be carried out for further investigation where necessary. This gives better picture of structure with small dimension that cannot be observed in aeromagnetic anomaly. However, access to site of investigation might be difficult especially during raining season Resource manager has to put every factor into consideration before decision is taking on which method is appropriate for mine project. For greatest measurement accuracy during ground survey, it is best to orient the magnetic sensor in the same direction at each station when acquiring the measurement.

Nabighian *et al*., (2005) explained that ground and airborne magnetic surveys are used at every conceivable scale and for a wide range of purposes. In exploration, they historically have been employed in the search for diverse commodities such as iron, precious metals, diamonds, molybdenum, uranium, titanium, iron oxide deposits, massive sulphide and heavy mineral sand. Every country has geological survey agency that responsible for compilation of airborne and ground data for national geophysical database. Airborne geophysical data can be acquired from the agency for research purpose which reduces cost and save time of carrying out a new survey which still required approval from the agency.

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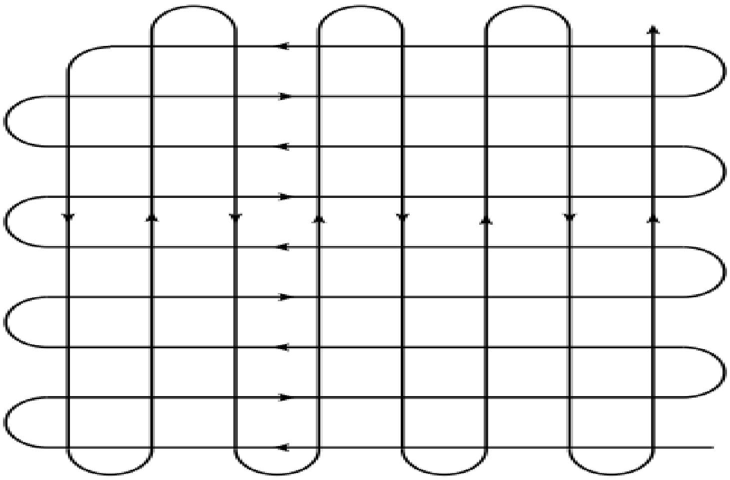

*Figure 1: Tracks of airborne magnetic survey (After Philip et al., 2002)*

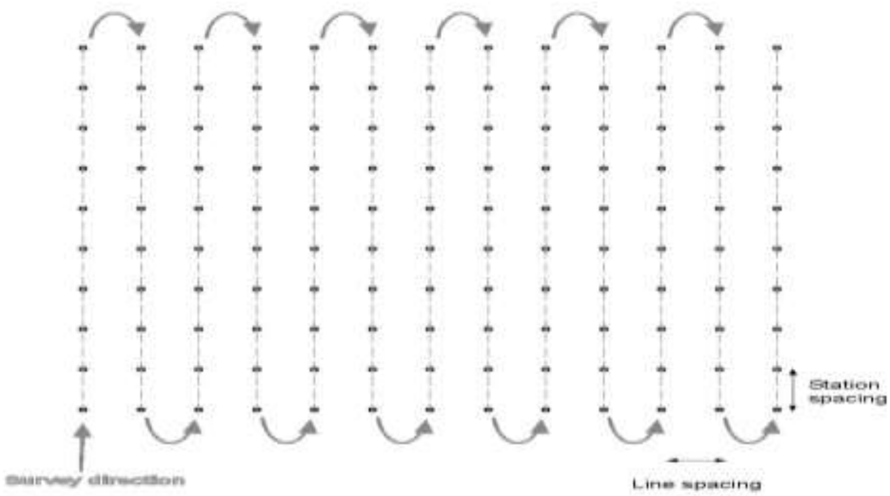


*Figure 2: Ground Survey grid pattern (After Geometric inc, 2007)*

*Table 1: Typical aeromagnetic data (Aeromagnetic data Sheet 245, Nigerian Geological Survey Agency)*

| X | Y | Z |
|---|---|---|
| 162560.2 | 826990 | 14.89136 |
| 171114.1 | 817394 | 20.70729 |
| 170946.1 | 829424.1 | 130.3956 |
| 163063.7 | 829567.8 | 109.0257 |
| 163734.6 | 829567.7 | 76.22852 |
| 164405.4 | 829567.6 | 29.36589 |
| 165747.1 | 829567.5 | 22.16912 |
| 167088.8 | 829280.9 | -27.3381 |
| 168095 | 829280.9 | 26.68672 |
| 168765.9 | 829280.9 | 39.2353 |

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***Table 2: Typical ground magnetic data (Adewuyi, 2011)***

| MARK | X | Y | READING | TIME | DATE | LINE |
|---|---|---|---|---|---|---|
| 155 | 55.000 | 0.000 | 33006.400 | 14:16:02.00 | 02/22/11 | 11 |
| 154 | 55.000 | 10.000 | 33008.800 | 14:15:33.00 | 02/22/11 | 11 |
| 153 | 55.000 | 20.000 | 33012.600 | 14:14:39.00 | 02/22/11 | 11 |
| 152 | 55.000 | 30.000 | 33016.000 | 14:13:47.00 | 02/22/11 | 11 |
| 151 | 55.000 | 40.000 | 33015.500 | 14:13:12.00 | 02/22/11 | 11 |
| 150 | 55.000 | 50.000 | 33016.500 | 14:12:28.00 | 02/22/11 | 11 |
| 149 | 55.000 | 60.000 | 33015.100 | 14:12:01.00 | 02/22/11 | 11 |
| 148 | 55.000 | 70.000 | 33016.500 | 14:11:06.00 | 02/22/11 | 11 |
| 147 | 55.000 | 80.000 | 33017.200 | 14:10:29.00 | 02/22/11 | 11 |
| 146 | 55.000 | 90.000 | 33015.900 | 14:10:00.00 | 02/22/11 | 11 |
| 145 | 55.000 | 100.000 | 33014.700 | 14:09:26.00 | 02/22/11 | 11 |
| 144 | 55.000 | 110.000 | 33015.200 | 14:09:03.00 | 02/22/11 | 11 |
| 143 | 55.000 | 120.000 | 33011.500 | 14:08:02.00 | 02/22/11 | 11 |

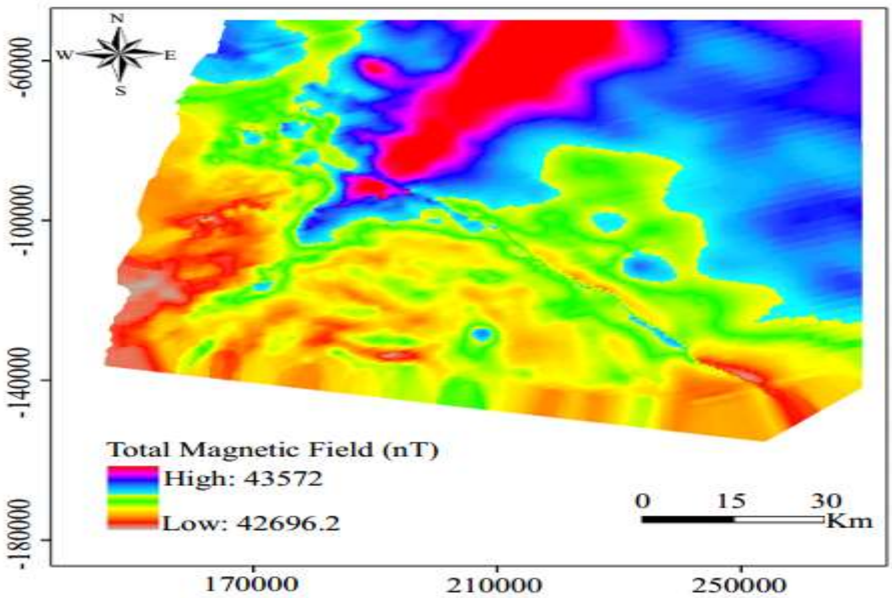


***Figure 3: Total magnetic field map (After Al -Amoush et al., 2013)***

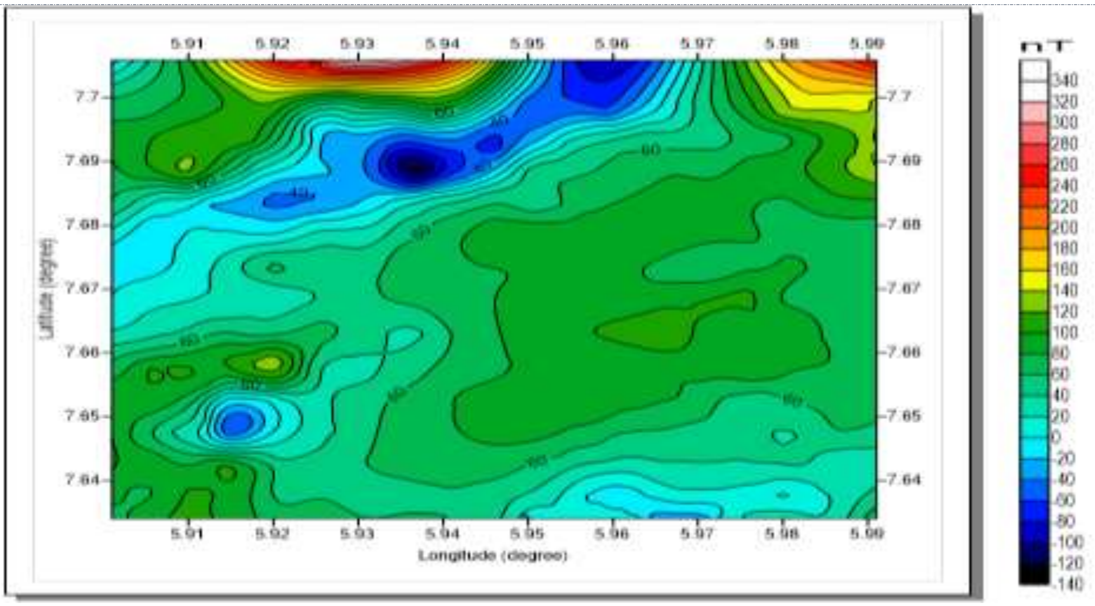


*Figure 4: Contour map of Akunnu Akoko area of Ondo State, Nigeria using aeromagnetic data sheet 245 (After Joshua et al, 2017)*

*Figure 5: Magnetic measurement with proton magnetometer (Saudi Geological Survey)*

**Gravity method**

Rocks have variable densities as measured routinely in the geological function of mining operations. Local variation in the densities of rocks near the surface cause minute changes to the gravity field. Survey(2015), discussed that density depends on the proportional content of iron(Fe) and magnesium(Mg) bearing ore in the rock's main mineral composition. Therefore, the mean density rises due to an increase in the proportion of mafic minerals. Variation in densities are measured using gravimeter (Figure 5).

According to Stepanov*et. al.*, (2015),surveys of gravity anomalies from aircraft (airbornegravimetry) have become common practice in recent years. Airborne gravimetry is a highly productive and inexpensive method of survey, which can be employed even in hard to reach areas. However, it must be noted that gravity method is expensive compared to magnetic method because of different corrections that must be applied to the observed data. Among the corrections are: latitude, the free-air and Bouguer corrections.

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*Figure 5: Land gravimeter (After Henry, 2010)*

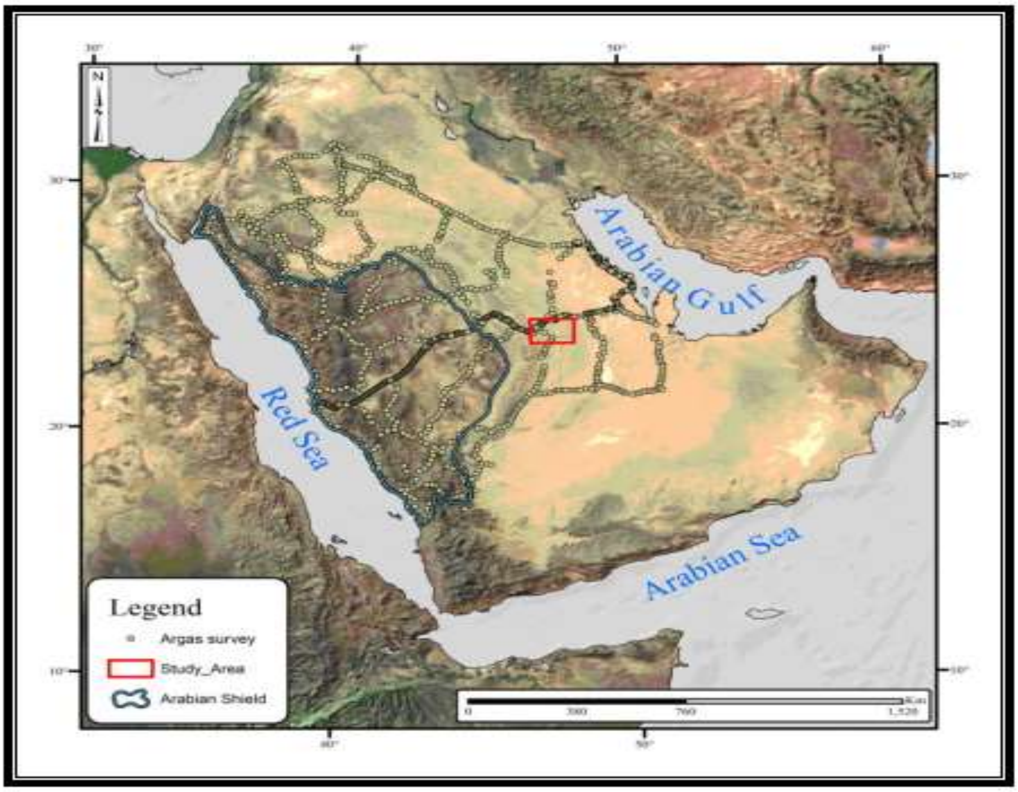


*Figure 6: Regional Gravity survey profiles in Saudi Arabia (After ARGAS)*

**Electromagnetic method (EM)**

Electromagnetic surveying is an excellent mapping technique which allows full 3-D mapping. Conductivity of geological structure can be obtained by measuring signals at different frequencies or in instantaneous time interval. Thus, permitting the conductivity at different depths to be computed for ore deposit. Sheard et al., (2005) discussed that the accuracy and ease of computation depend on the source geology configuration. They further expressed that with reasonable assumptions, a conductivity depth image (CDI) can be constructed, if measurements are taken at close enough intervals. Survey, (2015), discussed that EM is capable of directly

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detecting conductive base-metal deposits. He expressed that EM method is traditionally applied for prospecting of low-resistivity (high-conductivity) massive sulphide deposits.. Also, according to Zhdanov(2010), this methods has been successively applied in the exploration for massive sulfide orebodies and disseminated metal ores.

**Ground Penetrating Radar (GPR)**

According to Bernatek-Jakiel & Kondracka, (2016) ground GPR is an electromagnetic geophysical method to acquire information on subsurface materials based on high frequency (25 MHz–3 GHz) electromagnetic wave propagation. A common GPR system consists of transmitter and receiver antennas (shielded or unshielded) that are moved across the terrain surface. GPR is a geophysical method for non-destructive detection of ground layers by electromagnetic waves. GPR measures the two-way travel-time of the reflected electromagnetic wave propagating through the ground layers (Pupatenko et al., 2017).Daniels, (2009) asserted that GPR has been proved to be an effective non-destructive tool for solving a variety of engineering tasks. Pupatenko et al., (2017) retrated that the benefits of the method include development of a continuous GPR section, high efficiency and low cost. However, Culshaw et al., (2000) are of the opinion that the cost of the survey may be significantly higher than that of a magnetic or electrical conductivity survey.

**Electrical Resistivity Method**

Kowalczyk et al., (2017) retraited that electrical resistivity survey is characterized by high efficiency in prospecting, because it is a parameter that perfectly reflects the diversity of a geological medium in terms of lithology. Electrical resistivity survey can be carried out using a terrameter. Survey, (2015) discussed that the purpose of direct current (DC) electrical survey is to determine the subsurface resistivity distribution of the ground, which can then be related to physical conditions of interest such as: lithology, porosity, the degree of water saturation, and the presence or absence of voids in the rock. He further explained that during a resistivity survey, DC current is driven through the earth between pairs of electrodes installed at the surface or buried at depth. While current flows, electric potential differences are measured between other pairs of electrodes. The measured potential differences are related to there sistivity structure of the ground through which the current flows. The data acquired from the survey when analyzed, gives the structural geology of the location and associated mineral deposit can be detected. Although the use of electrical resistivity imaging (ERI) does not obviate drilling of exploration boreholes, they do allow streamlining drilling programs, which aids to significant reduce cost. Zarroca et al., (2015) discussed that ERI is an attractive exploration tool, as it may provide information of key subsoil features at a resolution suitable for many geo-engineering applications and capable to agreeing the logistical, schedule and economic constraints.

**Seismic Method**

Although seismic surveys are mainly employed for hydrocarbon exploration, there have been some recent applications to mineral exploration. Scott, (2014) discussed that massive sulphide bodies have higher seismic velocities than their host rocks, thus give rise to strong reflections. The first successful 3D seismic delineation of blind massive sulfide deposit was reported from the western part of the Bathurst mining camp, in the Half mile Lake area, Canada, at a depth of about 1.2 km (Malehmir et al., 2012). According to Koivisto et al., (2015)seismic methods are likely to be cost-effective only for massive sulphide and iron bodies.

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## III. METALLIFEROUS DEPOSITS AND PROSPECTING

Metalliferous mining has historically relied largely on geological mapping, drilling, and assaying techniques to define ore reserves and explore for further resources in the vicinity of a mine(Survey, 2015).Metalliferous mining involves detailed exploration and careful planning before opening up a mine, particularly an underground mine. Dai et al., (2015) discussed that non-metallic mineral can also contain metallic content. In the case of coal deposit with metal content, they named it "metalliferous coal". They discussed further that, concentrations of rare metals in ashes of some metalliferous coals are equal to or higher than those found in conventional types of rare metal ores and much higher than those in common coal ashes and associated sedimentary rocks.

All metals are electrically conductive in abroad sense, but the conductivity of an oredeposits primarily lies with sulphides orgraphite. The size, orientation and depth extent of a mineral deposit are the main factors with regard to geophysical expressions.(Survey, 2015). Geophysics has played a vital role in mineral exploration for many years but has not been conventionally regarded as a mining tool. The limited use of geophysics in metalliferous mines can be attributed in part to the relative complexity of the geology, and hence greater degree of uncertainty in interpretation(Fallon et al., 1997). In contrast to metalliferous mines, geophysical techniques are already well-established and delivering cost benefits in coal mines (Fallon et al., 1997).Many difficulties are involved in the exploration of metallic ores. Metal orebodies are relatively small but valuable, and many noneconomic minerals can masquerade as conductive orebodies(Zhdanov, 2010). Hence, it is important to have competent hands in every mining industry who have in-depth knowledge of difficulties involve in exploring metalliferous deposits in order to overcome the challenges and save cost. Also, great effort is needed to select appropriate method to discover metalliferous deposit.

Fallon et al., (1997) expressed that geophysical logging for orebody delineation is already delivering cost and time savings at a number of metalliferous mines around the world. The direct cost benefit flows from substitution of cheaper percussion andreverse-circulation drilling for core drilling. The time saving arises from the difference in drilling speed and from the reduced need for geological logging. This can only be achieved if relevant geophysical techniques discussed in chapter two has been used before drilling. As explained by Rudenno (2012), diamond core drilling (DCD) provides the best drilling results but it is the most expensive. It must be noted that larger cores provide better data but equipment is very expensive and consumes large amount of power. Hence, appropriately use of geophysical methods would ameliorate these challenges. The success of any geophysical exploration lie on adequate planning, appropriate method selection, competent hand for data acquisition and sophisticated tools for data interpretation.

***Table 3: Metalliferous minerals and their chemical composition***

| Element | Mineral | Chemical composition |
|---|---|---|
| Iron (Fe) | Hematite | $Fe_2O_3$ |
| | Limonite | FeO.OH |
| | Magnetite | $Fe_3O_4$ |
| Manganese (Mn) | Pyrolusite | $MnO_2$ |
| Chromium (Cr) | Chromite | $FeCr_2O_4$ |
| Nickel (Ni) | Pentlandite | $(FeNi)_9S_8$ |
| Molybdenum (Mo) | Molybdenite | $MoS_2$ |

**Magnetic method for prospecting metalliferous deposits**

Bayowa, O.G, et al, (2016) used ground magnetic data in conjunction with electrical resistivity data to establish occurrence of iron ore deposit at Tajimi village, Nigeria. Murthy et al., (2009) made use of magnetic method in exploration for Manganese ore deposit at Orissa, India. Brown and Vearncombe(2014) cited Miller and McLeod, (1999)for the use of magnetic data in gold exploration. Their paper reflected that drilling results targeting the gold deposit at Ghost Crab, Australia, was a disappointing one. This lead to the use of aeromagnetic data of the location which produce a good structuralre-evaluation of the gold mineralization in the area. If aeromagnetic method have been applied before drilling, it would have save cost of exploration. Though gold does not belong to metalliferous mineral but use of geophysical method prior to drilling would have save a lot of time, energy and money.

Lee and Abdoul-fatah (2002) carried out magnetic survey in conjunction with gravity and electrical imaging techniques at the Bedong, Kedah, on sites which had been mined for iron ore as well as areas adjacent to them. The geophysical methods detected a previously unknown probable iron ore (hematite with minor amounts of magnetite) deposit adjacent to the previously mine site. Though, they recommended the use of seismic method for further studies in the area and probably drilling strategic area using their results to identifying area needed to be drilled. Aaron, et al. (2015) used magnetic method to delineate iron ore deposit at Mutomo-Ikutha, Kenya. Chemical analysis was carried out on some sample at the site indicate 35% - 96% of iron content. The use of magnetic method for molybdenum was reported by Nguyen B. D., et al., (2014). This shows that magnetic method is very versatile in prospecting metalliferous deposits.

**Gravity method for prospecting metalliferous deposits**

Airborne gravimetry is a highly productive and inexpensive method of survey, which can be employed even in hard-to-reach areas (Stepanov, et al., 2015). Armstrong, (2006) discussed that airborne gravity gradiometer technology has been successfully used to explore iron ore.Lee and Abdoul-fatah (2002) as discussed section 3.1 combined gravity with magnetic method to prospect iron ore deposit. Alfred et. al., (1995) used gravity method with electrical, magnetic and electromagnetic methods to delineate chromite ore deposit at Albania.

**Electrical Resistivity Imaging (ERI) method for prospecting metalliferous deposits**

According to Zarroca et al., (2015), ERI technique enables researchers to cover broad areas, gathering large data sets that encompass thousands of apparent resistivity records, at a reasonable cost. ERI survey may complement subsoil explorations without increasing its budget. ERI does not obviate drilling of exploration boreholes, they do allow streamlining drilling programs, which aids to significant cost reductions. Accordingly, ERI was shown as an attractive exploration tool, as it may provide information of key subsoil features at a resolution suitable for many geo-engineering applications and capable to agreeing the logistical, schedule and economic constraints. Mubarik and Muhammad, (2013) used resistivity, gravity and magnetic methods for exploration of chromite ore deposit at Oman. They reported that mining operation have been performed in the area through conventional pitting procedure but remained unsuccessful. Whereas, integrated geophysical approach revealed the existence of chromite in the same area but on a different location. This shows the importance of geophysical techniques in metalliferous prospecting.

**Seismic method for prospecting metalliferous deposits**

Fallon et al., (1997) discussed that seismic method is the most widely applied geophysical imaging technique in metalliferous mines. An array of three-component 'microseismic 'receivers positioned within and surrounding the mine environment records the location of rock bursts usually to better than ± 5 m in absolute terms(Fallon et al., 1997).

**Electromagnetic method for prospecting metalliferous deposits**

Very low frequency (VLF) electromagnetic, gravity, and magnetic methods were used by Animesh et al (2015) for the exploration of Chromite deposit in the Sukinda belt, Odisha, India. They discussed that magnetic susceptibility of laterite (host of chromite in the study area)is comparable with chromite bodies thus, magnetic data alone are not reliable in this laterite covered study area to identify the possible chromite horizons. In the process of justifying while VLF electromagnetic method was included in their research, they explained that porous, impermeable and dry laterites (as found in the study area) are resistive in nature, while the presence of metallic minerals (chromites) in laterites makes them conductive. Also, resistivities of the host mafic/ultramafic and lateritic rocks are very high in comparison to chromite ores. Hence, VLF electromagnetic method is appropriate for their study. In addition, density of host mafic/ultramafic varies from 3000–3600 kg/m$^3$ and that of the chromite varies from 4430 kg/m$^3$ to 5090 kg/m$^3$, this makes gravity method also appropriate for chromate exploration.

According to Bayrak (2002), exploration for chrome ore deposits is complicated, hence it required integrated geophysical approach. He used VLF-EM, induced polarization (IP) gravity, magnetic and self - potential (SP) data for the exploration of chromite deposits in Southwestern Turkey. In his research, he considered VLF-EM has the primary method for chromite exploration. However, geology of location of investigation determine which method is most suitable for specific exploration. In the process of finding better, alternative, and economical method for exploration of chromite deposits, Ziaii et al., (2017) introduced opto-geometric image analysis (OGIA). Their method is a welcome development but it is only applicable at site with traces of chromite outcrop. In some cases, mineral deposit does not show at the surface hence, the use of geophysical methods cannot be ignored.

## IV. DISCUSSION AND CONCLUSION

Geophysical method has played indispensable role in mineral exploration. Researchers report of mining activities without carrying out geophysical studies but lead to waste of energy and monetary resources. This implies that, proper planning is lacking in part of regulatory body and some mining industries. The regulatory body should ensure that proper exploration has been carried out and report available in line with international best practice. Also, illegal mining activities should be checked and measure need to be put in place to curtail it. On the part of mining industries, refresher courses is necessary for all employees but special attention for mine planners. Mine planners need up till date information about new development and advancement in technology. Furthermore, effort is necessary to hire competent geophysicists to assist the company in the aspect of prospecting for new reserves since resources is finite.

According to available information base on papers reviewed in this research, magnetic method is the widely use geophysical method. It is usually used as primary method or combined with other geophysical methods in metalliferous exploration. Geological complexity does not allow the use of only one method, hence two or more methods is strongly advice for metalliferous prospecting.

The current level of development in the sphere of geo-survey does not allow for the complete abandonment of costly and labor intensive conventional survey techniques, such as boring. Nevertheless, in the near future geophysical methods will be able to provide complete information on the object of investigation (Pupatenko et al., 2017)

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