Advanced Geophysical Methods and Their Applications in Mineral Exploration

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ABSTRACT

Geophysical techniques have wide range of applications mainly in earth science, marine science, Civil Engineering and Forensic Science. For example in earth science they are applied in Geology, Mining Engineering activities, and Petroleum Engineering. However, publications and contributions regarding details and the state of art of each application are still scattered. This becomes more obvious when knowing that majority of publications discuss application of geophysical techniques for a particular mineral deposit with minimum trials to collect data together for understanding of the whole story. Therefore, this paper aims at review of available literature related to geophysical methods application in mining engineering with the purpose of assisting concerned professionals towards decision making. Findings reflected that magnetic technique is the most widely used method in minerals exploration while magneto-telluric method is not commonly applied in mining application. Collected results also showed that usually more than one geophysical method should be applied to arrive a robust conclusion concerning an in-depth existing ore deposit.

KEYWORDS: Mineral deposits; ore; mining; geophysical techniques; Exploration.

1. INTRODUCTION

Geophysical exploration belongs to the branch of geophysics that uses non-destructive approach to investigate mineral deposits (Teixidó, 2012). The applied Geophysical technique depends mainly on physical properties of rocks and their forming minerals beneath the earth surface. Mineral deposits exploration requires geophysical techniques to identify and estimate the deposit extension, borders, quantity in addition to its quality before embarking on mine operation (Boszczuk et al., 2011). Exploration research is a continuous process in mineral industries because reserve which is the asset of the industries is finite and nonrenewable. Also, near surface mineral is becoming more rarer and deep seated mineral target is now a major issue in mineral industries which required sophisticated geophysical techniques (Boszczuk et al., 2011). Geophysical techniques have wide range of applications mainly in earth science, marine science, civil engineering, hydrology, archeology (Teixidó, 2012)and Forensic Science. For example in earth science they are used and applied in Geology, Mining Engineering activities, and Petroleum Engineering. Historically, geophysical technique (magnetic) was first used in Sweden in the 17th century for prospecting iron ore (Reedman, 1979). Geophysical techniques gained more acceptability in the early 1923 (Gupter, 1986) because of exploration for crude oil. Relevance of Geophysics across the world is as a result of oil and solid mineral exploration. Early history of seismic technique can be found in the research of (Schriever, 1952). Historical development of magnetic technique in mineral exploration was discussed by (Nabighian et al., 2005).Application of Geophysics in mining is not a new field of study, though mining industries have not been able to judiciously harness its benefit very well. Much effort has been made by researchers to discuss applications of geophysics in mining but geophysical techniques are still been used below optimal capacity. However, increase in recognition of geophysical techniques in mining industries have been recently reported by (Galdón et al., 2017a). The use of geophysical techniques for exploration of metalliferous deposit was discussed by (Fallon et al., 1997) but other applications of geophysics in mining was left out in their study. Also, (Nabighian & Asten, 2002) reviewed the state of art in metalliferous mining geophysics without given information relating to non-metallic minerals and other applications of geophysical techniques in mining. Useful information and technical knowhow of geophysical technique in coal mining was

discussed by (Peter, 2013) but other applications in mineral deposits exploration were not discussed. Hence, framework and applications of geophysical techniques in mining is scattered which necessitate this research. This paper therefore, reviewed the previous works and discussed the applications of geophysical techniques in mining (metallic ore, non-metallic ore and other area of mining). Moreover, cost implication of geophysical data was presented.

2. CLASSIFICATION OF GEOPHYSICAL TECHNIQUES

Geophysical techniques can be classified on different bases. Firstly, they may be classified into passive and active techniques based on signal propagation via investigated ore (Reynolds, 1997). In Passive methods, signal are not required to pass into or penetrate the earth subsurface while in active methods generated signals always pass into or penetrate the subsurface before geophysical data can be obtained. The different methods included in each category are presented in Table 1.

Secondly, geophysical methods are classified according to the way they collect data which can be either by logging through boreholes or taking images from the ground surface (Fullagar & Fallon, 1997). They are typically named in literature as borehole logging geophysical techniques or geophysical imaging techniques. Borehole logging is the technique used in gathering information relating to mineral deposit from drilling of core in target identified resource zone. In contrast, geophysical imaging is used to acquire data at the surface of the earth using appropriate technique related to variation in physical properties of mineral and surrounding rocks. The first category includes: mechanical methods (caliper and sonic loggings), electrical method (resistivity, conductivity, self-potential and induced-potential), magnetic susceptibility logging, radioactive logging (natural gamma logging and neutron porosity logging), temperature logging and pressure logging, (Ofwona, 2014; Tittman, 1987) meanwhile the second category is as listed in Table (1). However, this paper only covers geophysical imaging techniques in Mining Engineering application.

In a third view, geophysical techniques were categorized based on physical property they use in identification of the unknown ore deposit in the earth (Gerhard, 2005; Yue, 2015). Classification of geophysical techniques by Yue (2015) was somehow different from earlier classification by Gerhard (2005) although they used the same approach. Potential was used to group magnetic and gravity by (Gerhard, 2005). However, the two authors left out radiometric and magneto-telluric techniques in their classification and therefore included in this paper. The details of the later and former with bases of classification were discussed under section 3.3 and 3.5 respectively.

3. APPLICATIONS OF GEOPHYSICAL TECHNIQUES IN MINING

Magnetic techniques

Magnetic technique has been the oldest geophysical method. During middle ages, compass and middle was used in detecting magnetic mineral especially magnetite (Milson, 2003). Advance in technology has led to production of different types of instrument (magnetometers) for measuring variation in susceptibility of mineral deposits. Magnetic data acquisition can be perform in air, on sea and land (Reynolds, 1997). Magnetic technique is the most commonly used geophysical tool in gold exploration, as it is in exploration for other metals (Doyle, 1990). Successful use of magnetic technique for gold exploration in South Africa and Canada was reported by (Hugh, 1990). Magnetic method has been used in coal exploration. As discussed by (Thomas *et al*., 2016), rare-metals (RM) have low magnetic response but intrusive host rocks which has high magnetic response make it possible to use magnetic technique for their exploration. Aeromagnetic method has been used in diamond exploration for decades (Frederick, 2002). Aeromagnetic data can be used for large scale exploration and more cheaper compared to ground magnetic survey but ground magnetic method give higher resolution of features. Other area where magnetic method has been applied alone or with combination of other methods area listed on Table (2).

Based on information from Table (2) and physical characteristics of mineral deposits, different geophysical methods are suitable for mineral exploration. However, some methods are more suitable than other for specific mineral deposits. In some cases, two or more methods can be suitable for the same mineral deposits depends on physical characteristics of the ore body (Table 3).

Gravity techniques

Gravity technique measures density contrast between mineral and surrounding rocks. Gravity technique based its principle on the Newton's law of gravitation "The Newton's law of gravitation states that the force of attraction, F between two masses m_1 and m_2, whose dimensions are small with respect to the distance, r between them then, F is directly proportional to the product of the masses and inversely proportional to square of the distance between them" (Association for Mineral Exploration British Columbia, 2013). Extrusive igneous rocks have the highest density follow by metamorphic rocks and intrusive igneous rocks while sedimentary rocks have lowest density. Density of rocks increases down the earth surface due to effect of pressure been exerted by the rock and soil near the earth surface. Details framework of gravity technique for gold exploration in South Africa was reported by (Doyle, 1990). The method has also been reported for chromate, iron, manganese, copper sulfides ore, and coal exploration (Table 2).

Table 1: Classification of geophysical techniques as per signal generation

Classification	Method	Principle	Depth of penetration	Survey method	Source
Passive	Magnetic	Measures variation in susceptibility of mineral deposits	0-20 km (ground data usually gives lower depth)	Ground, sea, airborne	(Kamil, 2008; Reynolds, 1997)
	Gravity	Measures density contrast of mineral deposits	Entire earth (ground data usually gives lower depth)	Ground, sea, airborne	(Kamil, 2008; Reynolds, 1997)
	Magneto-telluric (MT)	Measures electrical conductivity of minerals and rocks	0-150km (practical depth is 0.1 - 100km)	Ground	(Kamil, 2008)
	Radiometric	Measures the emission of gamma ray (ɣ-ray) from radioactive elements in mineral deposits	0 – 0.305 km	Ground, airborne	(Nelson, 1949)
Active	Electrical resistivity	Measures electrical conductivity of minerals and rocks	0 - 0.1km (practical depth is < 0.3km)	Ground	(Kamil, 2008)
	Electromagnetic	Measures electrical conductivity of minerals and rocks	0 - 10km (practical depth is < 5km)	Ground, airborne	(Kamil, 2008; Reynolds, 1997)
	Ground penetrating radar (GPR)	Measures variation in dielectric constant of mineral deposit	0-0.05km (results become less reliable after 10m)	Ground	(Kamil, 2008)
	Induced - Polarization (IP)	Measures the electrical capacitance of minerals	0 - < 0.3km	Ground	(Kamil, 2008)
	Self-Potential (SP)	Measure electrical conductivity of minerals and rocks	0 - 0.03 km	Ground	
	Seismic	Measures the arrival time of wave penetration through rock media	0 - 10km for reflection, 0 - 150km for refraction	Ground and sea	(Kamil, 2008)

Electrical techniques

Geophysical methods that measure electrical physical parameters are grouped together as electrical techniques. Electrical resistivity, electromagnetic, magneto-telluric and self-potential methods measure electrical conductivity of minerals and rocks. Induced polarization measures the electrical capacitance of minerals while GPR measures variation in dielectric constant of mineral content. Among electrical methods, resistivity technique is the most applied in mineral exploration (Survey, 2015) using terameter. As discussed by (Kowalczyk et al., 2017) some of the physical conditions that affect the geological media are; amount of void, water saturation, porosity and lithology. Resistivity of minerals and surrounding rocks are dependent on those physical conditions as well as structure and texture of contained minerals. It is well known that areas of low resistivity are usually produced by sulfides, graphite, and salty overburden (Doyle, 1990). Apart from mineral investigation, resistivity technique is also being use in geotechnical study to estimate depth to bedrock and landslide related research.

As reported by (Survey, 2015), electromagnetic (EM) technique in most cases is use for exploration of low-resistivity massive sulphides mineral deposits. Data acquisition using EM can be done in air and on ground, unlike other electrical methods that can only be carried out on ground. Detail history of EM can be found in a research by (Zhdanov, 2010).

As discussed by (Markus, 2017), SP method was proposed by Robert Fox in 1830 at Cornwall, England. SP is usually adopted in sulphide and graphite mineral exploration. Comprehensive information about SP data acquisition has been published by (Charles et al., 1983). Induced polarization has been reported for prospecting of metallic sulphide deposits as far back as 1990 by (Doyle, 1990). IP like SP is well known for exploration of metal sulphides(Scott, 2014; Survey, 2015; Tavakoli et al., 2012, 2016). The use of IP technique for gold exploration at Abitibi greenstone belt, Canada was reported by (Doyle, 1990). However, responses of gold target to IP usually are of low amplitude.

Table 2: Ore exploration and geophysical techniques

Country	**Location**	**Ore type**	**Method**	**Source**
Australia	Ghost Crab	Gold	Aeromagnetic	(Miller & McLeod, 1999)
China	Tuwu,	Gold	Seismic reflection	(Tonglin & David, 2005)
Australia	Agnew, Western ,	Gold	Gravity, aeromagnetic and IP	(Nigel, 2003)
Canada	British Columbia,	Gold	Seismic data	(Roy & Clowes, 2000)
Iran	South Khorasan,	Gold	Magnetic method	(Haidarian Shahri et al., 2010)
Canada	Halfmile Lake area	Sulfide deposits	Seismic reflection	(Malehmir & Bellefleur, 2009)
Albania	-	Copper sulphide ore and Chromite	Electrical, gravity, magnetic and electromagnetic methods	(Alfred et al., 1995)
Oman	-	Chromite	Gravity, magnetic and resistivity	(Mubarik & Muhammad, 2013)
India	Odisha,	Chromite	Electromagnetic, gravity, and magnetic methods	(Animesh et al., 2015)
Turkey	Southwestern	Chromite	Electromagnetic, IP, gravity, magnetic and SP	(Bayrak, 2002)
Malaysia	Pagoh, Johor,	Iron ore	IP and DC resistivity	(Bery et al., 2012)
Nigeria	Tajimi village,	Iron ore	Magnetic and electrical resistivity	(Bayowa et al., 2016)
Brazil	São Sepé city,	Iron ore	Electrical resistivity and IP	(César et al., 2016)
Kedah	Bedong area,	Iron ore	Magnetic, gravity and electrical methods	(Lee, 2002)
Kenya	Mutomo-Ikutha,	Iron ore	Magnetic method	(Waswa et al., 2015)
Indonesia	Aceh Jaya,	Manganese ore	Magnetic method	(Walid & Adi, 2013)
India	Orissa,	Manganese ore	Gravity, magnetic and electrical resistivity methods	(Murthy et al., 2009)
China	Shangri-La,	Molybdenum ore	Magnetic method	(Nguyen et al., 2014)
Nigeria	Itobe,	Marble Deposit	Resistivity method	(Onimisi et al., 2015)

According to (Wai-Lok Lai et al., 2018), GPR gained acceptability for mineral exploration around 1950. Since then, it has been used for exploration of different mineral deposits and for mine waste hazard investigations. GPR based its principle on electromagnetic wave such that, frequency signals are transmit and then receive after penetration through the target area using appropriate GPR devices to measure the dielectric contrast of the minerals. The signal frequency is usually in the range of 10 - 5,000 MHz, 10-10,000 MHz (Wai-Lok Lai et al., 2018) or 100 MHz – 1GHz (Galdón et al., 2017b) depend on dimension of emitting and receiving antennas. The electric and magnetic properties of minerals determine the speed, attenuation and polarization of signal through minerals and surrounding rocks. GPR has numerous application in mining such as; investigation of hang wall thickness, rock fractures, potholes, ore zone exploration (Francke, 2012) and old mine (Galdón et al., 2017b).

However, it works well for shallow mineral investigation because, its depth of penetration is very small compare to other geophysical methods and requires higher radar frequencies to get good resolution.

Magneto-telluric technique (MT) was first proposed by Cagniard (1953). It uses earth's magnetic field variations and induced telluric currents as a result of electric field to measure the electrical resistivity of minerals and rocks. This method was actually developed for prospecting deep seated mineral deposit (several kilometers) but it is rarely used because most deep seated mineral deposits are not being mined economically (Reedman, 1979). The technique seems best suited to soundings sedimentary layers. However, the possibility to apply the MT technique in the search for shallow deposits was opened by the widespread introduction of the high frequency modification of the method, the audio magneto-telluric (AMT) sounding. Despite advance in technology, MT alone cannot be used for mineral exploration and it is highly costly (Varentsov et al., 2013). Also, new MT data interpretations need to be developed to make analysis easier. More information about magneto-telluric can be found in a paper by (Aboud et al., 2014).

Table 3:Geophysical techniques in mining related research (Most appropriate Δ, appropriate or may be applied •)

Method	Gold	Iron ore	Copper	Diamond	Sulfide	Manganese	Molybdenum	Chromate	Bauxite	Coal	Limestone	Marble	Phosphate	Uranium	Fault zone	Rock slide	Waste dump
Magnetic	•	Δ	•	•	•	Δ	Δ	Δ	•	•			•	•	•		•
Gravity	Δ	•	•	Δ		•	•	•	•	Δ	•		•		•	•	•
Resistivity		•	Δ		•	•	•	•	Δ	•	Δ	Δ	•		Δ	•	•
EM	•	•	•	Δ	•	•	•	•		•		•				•	•
IP	•	•			Δ	•		•									
GPR				•								•			•	Δ	Δ
SP		•		•	Δ			•		•						Δ	•
Seismic	•			•	•				•	Δ	•		•		Δ	•	
Radiometric													Δ	Δ			•

Seismic techniques
Seismic methods when applied, measure the arrival time of wave that have travelled through the elastic media or rocks from the source (hammer or detonation of dynamite) at the surface to the receiver (geophones). The variation in density of minerals and rocks make the velocity of wave differ from one point to the other. Also, the arrival time of the wave differs depend on the density of the media. Seismic techniques are mostly being use in exploration for oil and gas but also have some applications in mining industries especially for locating metallic ore deposits in sedimentary basin. Seismic techniques are also applicable for investigation of basement depth and crustal structure of underlain rocks. The approach has been applied to determine the background condition in coal mine (Fallon et al., 1997; Zou et al., 2013) and salt cavities (Kosecki et al., 2009). As illustrated in Figure (2), seismic techniques are of two type; reflection and refraction. The formal base its principle on law of reflection of wave while the later based its principle on law of refraction of wave. Data acquisition can be carried out on land or sea by creating vibration using explosive material.

Radiometric technique
Radioactive technique involves measuring the emission of gamma ray (ɣ-ray) from radioactive elements using Geiger-Muller or scintillation counter. The data can be taken on ground and in air (airborne radiometric survey). Radioactive elements are unstable in nature and they disintegrate to form daughter isotopes at a specific rate of decay. Radiometric technique is a well know approach in exploration for nuclear minerals. It can be used in exploration for potassium, thorium, uranium, carbon and rubidium. Apart from exploration applications of radiometric technique, it can also be used in radon assessment in underground mining to prevent radiation hazard (Adagunodo et al., 2018; Bochiolo et al., 2012; Gaafar et al., 2016; Kaniu et al., 2018) for workers at mine sites.

4. DISCUSSION

It was observed that most geophysical techniques measure electrical properties of the rocks and mineral to unravel ore deposits. The resistivity method is used to map spatial variations in subsurface electrical conductivity, while the induced polarization (IP) method is used to map variations in chargeability. Table (2) presents methods used by different researchers for ore prospecting. Research works presented in the table were selected based on available information. Table (3) presents appropriate methods that can be applied in mining exploration. Many authors failed to include area covered during their survey. It is highly important to present area covered during geophysical survey or give number of traverse and line with their space interval from which interested reader can get idea of area covered for future research. Table (2 and 3) clearly show that magnetic method has wide range of applications because it was applied in almost all research work presented and for different applications. Though, it is the oldest geophysical method but advance in technology makes it relevant in many area of geophysical, geological and mining research.

5. CONCLUSION

Geophysical methods has wide range of applications in many area of earth related sciences and engineering disciplines. Combination of more than two geophysical methods can provide better information to arrive at good conclusion. Geophysical surveys required in-depth knowledge of technicality involve in data acquisition, analysis and interpretation. Different method has distinct techniques, thus researcher must understand the procedures of the applicable method(s). The geophysical techniques in mining fields were reviewed and classification of different methods was revisited using physical parameters. Methods used by researchers in ore exploration were presented to be a guide for other researchers in mineral industries and related fields. Magnetic method happens to be the most widely used technique in mineral exploration while radiometric method has limited application because it is mainly for radioactive mineral exploration.

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