

Some Experiences of Resistivity and Induced Polarization Methods on the Exploration of Sulfide: A Review

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How to cite this paper: Dusabemariya, C., Qian, W., Bagaragaza, R., Faruwa, A. R., & Ali, M. (2020). Some Experiences of Resistivity and Induced Polarization Methods on the Exploration of Sulfide: A Review. *Journal of Geoscience and Environment Protection, 8*, 68-92.

https://doi.org/10.4236/gep.2020.811004

Received: September 27, 2020 Accepted: November 10, 2020 Published: November 13, 2020

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Abstract

Sulfide minerals are a group of compounds with the presence of sulfur. This group's most abundant and economically members are pyrites, pyrrhotite, chalcocite, galena, sphalerite, and the group of copper sulfides minerals. Resistivity and Induced Polarization (IP) methods, which play an essential role in mineral exploration, showed great success in sulfide exploration. This paper started on reviewing sulfide formation by giving details which help to understand their genesis better. To make the reader understand the procedures and appropriate mineral exploration methods, we have briefly covered the theory, the basic principles of resistivity and IP methods, and different investigation techniques using one, two, and three-dimensional surveys. Based on many electrical surveys, we discussed with examples of resistivity and IP methods applied to the exploration of sulfide deposits: the data inversion and interpretation of the geophysical signatures of most of the sulfide deposits in various geological environments were analyzed and end by showing both successful surveys and limitations of the methods.

Keywords

Resistivity, Induced Polarization, Chargeability, Sulfides, Mineralization

1. Introduction

Sulfide minerals are a group of compounds with the presence of sulfur. The most abundant and economically members of this group are pyrites, pyrrhotite, chal-

cocite, galena, sphalerite, and the group of copper sulfides minerals (Vaughan & Corkhill, 2017). It is difficult to distinguish between massive sulfides and other conductors of unknown character and to determine the direction of the orebody (Telford, Geldart, & Sheriff, 1990b). Electrical Resistivity Tomography (ERT) is the most commonly used geophysical methods for imaging subsurface features and map geological variations. It can detect subsurface sulfide mineral distribution by studying the nature of the flow of electricity in the earth, for being uniquely able to see a large range of magnitudes which can vary up to 20 orders (Morgan, 2012). This method can delineate the various sources of mineralization according to their types (Evrard et al., 2018). The resistivity method is used to map spatial variations in subsurface electrical conductivity, while the induced polarization (IP) method is used to map changes in chargeability.

A variety of applications of resistivity and Induced polarization to mineral exploration were demonstrated in many researchers and significantly prove their success by locating the best drilling points (Langore, Alikaj, & Gjovreku, 1989; Oldenburg & Li, 1994; White et al., 2001; Wilkinson et al., 2006; Qian et al., 2007; Bery et al., 2012; Loke et al., 2013; Dandi, 2014; Tavakoli et al., 2016a; Ali et al., 2020). The geological structures of occurrence of sulfide minerals show low resistivity and high chargeability (Johnson & Anderson, 1981; Langore, Alikaj, & Gjovreku, 1989; White et al., 2001; Yoshioka & Zhdanov, 2005; Ja, Oo, & Arce, 2014; Côrtes et al., 2016). The IP can detect information of small conductive rocks lost in the resistivity models (Tavakoli et al., 2016b). It is also able to detect sulfide in the presence of disseminated mineral deposit (Olowofela, Ajani, & Oladunjoye, 2008).

This review attempts to provide a clear summary of the success and problems encountered with resistivity and IP methods in sulfide mineral exploration. We focus on determining the efficiency of Resistivity and IP in exploring sulfide minerals by identifying their geophysical properties, the fundamentals of geophysics, and the host rocks by highlighting strengths and weaknesses. It also presents a brief discussion of the limitations of the electrical resistivity and IP methods.

2. Para Genesis of Sulfides

Sulfide can be formed abiotically or biogenically.

2.1. Abiogenic Sulfides Formation

Sulfide minerals can form abiologically through the crust at high temperatures above about 200°C (Plimer & Finlow-Bates, 1978; Trudinger, 1981; McDonald et al., 2018). High-grade sulfide deposition from abiogenic sulfide exhaled in hydrothermal fluids at oceanic spreading centres and rift zones (Trudinger, 1981). According to McDonald et al. (2018), Three phases are defined: The first is an early-stage of low-temperature (<250°C), dominated by Fe-Zn-Cu-rich mineralization, the second stage present high-temperature (>300°C) and is dominated by Cu-Fe-rich mineralization; and the third is at low-temperature phase (<150°C)

dominated by Fe-rich mineralization (McDonald et al., 2018). However, at this low temperature (120°C - 140°C), pyrrhotite can be found in a stable state (Plimer & Finlow-Bates, 1978).

Figure 1 shows the example of sulfides formation at high temperatures.

The older the deposit and the deeper its site of deposition, the more likely it is to contain abundant pyrrhotite, lack barite (Plimer & Finlow-Bates, 1978). Deposits which formed at shallow depth (<500 m) where circulation was probably restricted, pyrite is far more abundant than pyrrhotite (Plimer & Finlow-Bates, 1978).

2.2. Biogenic Sulfides Formation

In biogenic sulfides formation, bacteria activities are the primary source of sulfides. Bacterial sulfate reduction is a potential source of high sulfide concentrations in typical marine sediments. However, fixation is limited by a lack of reactive metals and could lead at best to the formation of relatively low-grade ores. Biogenic sulfide might also contribute to mineralization in hydrothermal situations (Trudinger, 1981). The sulfate reduction process takes place in much lower temperatures (<150°C) (Trudinger, 1981; McDonald et al., 2018). In hydrothermal systems, thermophilic bacteria biogenically reduce seawater sulfate (SO_4^{2-}) to sulfide (H₂S) (McDonald et al., 2018). When these react with Fe⁺₂, they can form a very fine particle black precipitates poorly crystalline mackinawite (FeS) or a mixture with greigite (Fe₃S₄). With time, these iron minerals transform into pyrite. Figure 2 indicates three possible pathways of transformations.

Table 1 shows examples of sulfide minerals and their host rocks from both abiotically and biogenically.



Figure 1. Genesis of volcanogenic massive sulfide deposits (Galley, 1993; Gibson et al., 2007; Piercey, Peter, & Herrington, 2015).



Figure 2. The pathways leading to the formation of pyrite. Formation of sulfide in Brunswick Number 12 (Piercey, Peter, & Herrington, 2015; Vaughan & Corkhill, 2017).

Types	Major ore Minerals	Examples
	Mafic host rocks	
Sulfide nickel deposits	po, pn, py, cpy, vio	Sudbury, Ontario Canada
Besshi-type massive sulfides	py, cpy, sph, gn	Japan
	Felsic host rocks	
Zinc-lead skarns	py, sph, gn	Ban Ban, Australia
Copper skarns	ру, сру	Carr Fork, Utah, USA
Polymetallic veins	py, cpy, gn, sph, ttd	Camsell River, NWT, Canada
	Felsic & mafic host rocks	
Creede-type epithermal	py, sph, gn, cpy, ttd, asp	Creede, CO, USA veins
Kuroko-type	py, cpy, gn, sph, ttd, asp	Japan
	Sedimentary host rocks	
Quartz pebble	U-gold py, uran, gold	Witwatersrand, RSA
Sandstone-hosted lead-zinc	py, sph, gn	Laisvall, Sweden
Sedimentary exhalative lead-zin	py, sph, gn, cpy, asp, ttd, po	Sullivan, BC, Canada
	Carbonate host rocks	
Mississippi Valley type	py, gn, sph	Missouri, USA

Table 1. The major types of sulfide ore deposits and host rocks.

Abbreviations used are as follows: po-pyrrhotite, pn-pentlandite, py-pyrite, cpy-chalcopyrite, viol-violarite, cass-cassiterite, sph-sphalerite, gn-galena, bn-bornite, ttd-tetrahedrite, asp-arsenopyrite, cinn-cinnabar, uran-uraninite (Fontboté et al., 2017; Vaughan & Corkhill, 2017).

3. Theory and Basic Principles of the Resistivity and IP Methods

3.1. Theory and Basic Principles of the Resistivity Method

The electrical resistivity surveys consist of measurement of the resistivity distri-

bution of subsurface heterogeneities. Electric current is generated into the ground, creating a stationary current flow in the earth. Potentials measured, produce features of the subsurface by providing information on their electrical properties.

For simplicity, all layers are expected to be horizontal. The electrical resistance, R of a material is related to its physical dimension, cross-sectional area, Aand length, L through the resistivity, ρ .

$$= RA/L \tag{1}$$

The electrical resistance of the cylindrical body $R(\Omega)$, is given by: R

$$=V/I \tag{2}$$

where V is the potential and I is the current.

The conductivity σ (Sm⁻¹), is the reciprocal of the resistivity.

$$\sigma = l/\rho \tag{3}$$

(White et al., 2001).

In a homogeneous and isotropic half-space, the current density $J(A/m^2)$ is:

$$J = I / \left(2\pi r^2 \right) \tag{4}$$

The potential V becomes:

$$V = \left(\rho I\right) / \left(2\pi r^2\right) \tag{5}$$

The measured voltage with the injected current is converted into apparent resistivity (ρ_a) by a geometric factor which considers the air-earth interface (Telford et al., 1990a)

$$\rho_a = k \frac{\Delta V}{I}, \left[\Omega \cdot \mathbf{m} \right] \tag{6}$$

where: *k* is a geometrical factor [m].

$$k = \frac{4\pi}{\frac{1}{r_{MA}} + \frac{1}{\dot{r}_{MA}} - \frac{1}{r_{MB}} - \frac{1}{\dot{r}_{MB}} - \frac{1}{r_{NA}} - \frac{1}{\dot{r}_{NA}} + \frac{1}{\dot{r}_{NB}} + \frac{1}{\dot{r}_{NB}}}$$
(7)

 r, \dot{r} are the distances of the real and mirror effect of the ground surface at potential points (M, N) respectively.

 ΔV is the measured difference potential at points M and N; I is the applied electric current.

3.2. Theory and Basic Principles of the IP Method

IP has been widely used in geophysical surveys for many decades to provide information about the complex conductivity (chargeability) of the subsurface. IP effect can be measured by both time-domain and the frequency domain. The most common is Time-Domain IP. When the current is applied to the ground, the ground can act as a capacitor and store electric charge. The imposed voltage is switched off; it first drops to an intermediate voltage and then gradually decays (Figure 3 and Figure 4). The polarization characteristics of the subsurface



Figure 3. Integrated decay voltage used as a measure of chargeability m.



Figure 4. Time window chargeability.

are produced by switch-off the transmitted current and measure the potential decay. This is known as the apparent chargeability (M). The most common measurement of the magnitude of the IP effect in the time domain is chargeability M.

The common chargeability expression is:

$$M_{a} = \frac{1}{V_{p}} \int_{t_{1}}^{t_{2}} V_{s}(t) dt$$
(8)

where V_p is the primary voltage, V_s represents secondary voltage, and V_t is the voltage decay with a time interval between t_1 and t_2 . Units of chargeability are millivolts per volt (mV/V) or millisecond (ms).

In the frequency domain, measurements involve measuring the resistivity at varying frequencies one higher than the other, transmitted one after the other. The IP effect is the percentage frequency effect (PFE) defined as:

$$PFE = \frac{\rho_2 - \rho_1}{\rho_1} * 100$$
 (9)

where ρ_2 and ρ_1 represent apparent resistivity at high and low frequencies respectively. PFE has units of percent.

The IP effect is influenced by the effective resistivity of the host rock and, consequently, by the type of electrolyte, pore size, temperature etc. Though, the metal factor (MF) can remove this effect to some extent (Telford, Geldart, &

Sheriff, 1990b).

Metal Factor is defined as the amount of sulfide minerals contained in rocks, in which the amount depends on the value FE. Metal factor is formulated as follows:

$$MF = 2\pi * 10^5 \frac{\rho_2 - \rho_1}{\rho_1}$$
(10)

1000 is an arbitrary factor chosen to give MF values appropriate values from 10 upwards, and MF has of mhos per foot.

The concept of metal factor arose early in the development of the IP method, because it was felt that low resistivity values would damp the value of PFE more than high resistivity values.

3.3. Characteristics of Different Arrays Configurations Types

Several conventional electrode arrays are used for resistivity and IP surveying. There is no "best" method that can match with all situations encountered in the fields (Daniels, 1977) but the choice depends on the aim of prospecting; the geological aspects of the subsurface, the availability of holes; and economics (Daniels, 1977; Bing & Greenhalgh, 2000). Table 2 describes common arrays configuration depending on the measured potential by assuming that the earth's resistivity is homogeneous and isotropic.

Surface configuration: Surface geophysical methods present a low spatial resolution, which decreases with increasing depth of investigation. Moreover, this can hinder the exposure of small-scale features such as cavities or leachate plumes. The use of electrodes in boreholes and pole-dipole arrays are recommended to extend the adequate depth of investigation (White et al., 2001).

Hole-to-surface measurements are performed by setting a pole or dipole source down a borehole and making surface dipole measurements away from the source hole (Daniels, 1977).

Borehole: Vertical profiles can detect both in-hole and off-hole features, but the enlargement depends on the configuration (Palich & Qian, 2007).

Single-hole arrays (Vertical Resistivity Profiling (VRP)) use a pole or bipole source and potential receiver in the same borehole (Daniels, 1977).

Hole-to-hole measurements (Borehole Resistivity Tomography (BRT)), this is performed by installing a pole or a dipole current source in a borehole and placing a pole or a dipole potential-receiver nearby borehole (Daniels, 1977).

The cross-borehole resistivity measurements seem to be more useful than single-borehole measurements (Yang & Ward, 1985; Wright & Ward, 1987; Qian, Milkereit, & Gräber, 2007; Ali et al., 2020). Qian, Milkereit, and Gräber (2007) reported the success of the cross-borehole method, where the imaging of the massive sulfide mineralization was more extended compared to the single borehole. However, the cross-borehole anomalies are smaller by using a pole-pole array than the dipole-dipole array. Though, with the cross-borehole mise-àla-masse method, the anomalies are more significant than other cross borehole methods (Wright & Ward, 1987).

Table 2. The common electrode arrays.

Array types	Measured potential	Advantages	Disadvantages
WENNER	$\rho = 2\pi \frac{V}{I}a$	High signal strength; Sensitive vertical variations	Poor horizontal coverage Less sensitive to 3D structures High voltage
SCHLUMBERGER	$\rho = \pi \frac{V}{I} n (n+1) a$	Sensitive vertical variations Better resolution for shallow	Poor horizontal coverage
THREE - ELECTRODE (POLE - DIPOLE)	$\rho = 2\pi \frac{V}{I} n(n+1)a$	Better target detection Suitable for targeting deep Good horizontal coverage High signal strength Less sensitivity Better data resolution	Many near-to-zero potential values Singularity problem in data acquisition Complicate the inter-pretation
DIPOLE - DIPOLE	$\rho = \pi \frac{V}{I} n(n+1)(n+2)a$	Better target detection Satisfies reciprocity No remote-electrode effects Very sensitive to horizontal variations Easy acquisition of field data in built-up areas. Most sensitive array to 3D structure	Insensitive to vertical variations Many near-to-zero potential values Singularity problem in data acquisition Decrease in signal strength with Often suffer from a poor signal-to-noise ratio
Pole-pole $a \forall B \Rightarrow a \forall B \forall B \Rightarrow a \forall B \forall B$		Widest horizontal coverage Deepest depth of investigation	Poorest resolution Remote-electrode effects Other electric sources can easily affect the data All the data do not meet reciprocity Systematic error into the inversion

(Edwards, 1977; Telford, Geldart, & Sheriff, 1990b; Furman & Ferre, 2003; Aizebeokhai, 2010; Tavakoli et al., 2016a; Hassan, Rai, & Anekwe, 2017).

For shallow targets hole- to-surface measurements may locate the target with a minimal field effort (Daniels & Scott, 1981; Daniels, 1983; Tsourlos et al., 2011). In the case of borehole-to-surface, Pole-dipole and dipole-dipole configurations are preferred because other arrays such as Wenner, Wenner-Schlumberger, and Gradient Schlumberger are more prone to artifact distortion (White et al., 2001; Tsourlos et al., 2011). The lateral position of the target can easily set by hole-to-surface or conventional dipole-dipole surface arrays (Daniels & Scott, 1981). Ideally, the horizontal position of the body can be established by a conventional surface survey or a hole-to-surface survey while the vertical position of the body can be determined by hole-to-hole or single-hole measurement (Daniels & Scott, 1981). For the intersection of mineralization and drill holes, mise-á-la-masse surveys appear more promising for imaging the minerals' orientation and strike extent (Tyne, 1980; Guo, Dentith, & Zhao, 2000). However, for near-surface with borehole resistivity surveys, accurate array locations and correct geometry factors are very important to account for borehole deviation effect and for accurate imaging (Guo, Milkreit, & Qian, 2014). For all, shorter electrode intervals are needed to better define shallow anomalies and mineralized veins (Mammo, 2013).

4. 1D, 2D, and 3D Imaging Surveys and Inversion Processes4.1. 1D, 2D, and 3D Dimensional Surveys

The Electrical Resistivity and IP methods can provide 1D, 2D or 3D images of their distribution in the subsoil.

4.1.1. 1D Dimensional Surveys

Since the early 1920s to the late 1980s, the resistivity method's first commercial use was one-dimensional (1-D) mapping method for the profiling and sounding methods (Ghosh, 1971; Ward, 1990; Meheni et al., 1996; Loke, 2011; Sharma & Verma, 2015). The method is quick and simple in application (Ghosh, 1971; Ogunbo, 2018), it has been widely used to investigate the ground for resource management, such as mineral, petroleum, and groundwater resources (Loke, 2011). With this survey, the subsurface should consist of horizontal layers (Loke, 2011; Loke et al., 2013). In homogeneous, 1-D survey provides good results (Karim, 2015). However, 1-D survey does not provide significant lateral changes, which may bring to gives inaccurate results or misleading results (Loke, 2011; Loke et al., 2013).

4.1.2. 2D Dimensional Surveys

2-D imaging surveys are mostly used in mineral exploration. Two-dimensional multi-electrode arrays produce simultaneous and display both horizontal and vertical variations in resistivity (Loke, 2011; Loke et al., 2013). Wenner, Wenner-Schlumberger, dipole-dipole, pole-pole or pole-dipole arrays are the most common use, depending on the respective position of the potential electrodes and the current electrodes.

The sensitivity to horizontal and vertical heterogeneities, depth of investigation, data coverage and signal strength change depends on type of configurations array and the background noise level (Samouëlian et al., 2005). Commonly 2-D inversion for resistivity data was used by many of the reviewed papers (White et al., 2001; Moreira et al., 2012; Goto et al., 2013; Mammo, 2013; Côrtes et al., 2016; Tavakoli et al., 2016b). **Figure 5** clearly shows the correlation of Resistivity and IP and their efficiency in 2D prospecting.

Figure 5 indicates that both resistivity and IP show a large contrast between the electrical properties of sulfide and their host rocks. The 2-D and 3-D forward interpretations are based on finite-difference, finite-element, transmission surface, integral-equation, or hybrid finite-element/integral equation formulation to provide a reasonable estimate of the subsurface structure (Zonge et al., 2014).

4.1.3. 3D Dimensional Surveys

3D modeling is now playing an important role in very complex exploration



Figure 5. Correlation of low resistivity and high chargeability in sulfide (Ja, Oo, & Arce, 2014; Kumar et al., 2016; Tavakoli et al., 2016b).

(Loke et al., 2013; Sharma & Verma, 2015). Three-dimensional electrical resistivity can be obtained by reconstructing a two-dimensional network of parallel pseudo-sections or using a square array of four electrodes (Bentley & Gharibi, 2004). Several studies show the effectiveness of the 3D survey compared to 1 D and 2 D. The 3D surveys perform well with high accuracy in short time (Bentley & Gharibi, 2004). When the dipole-dipole or pole-dipole electrode array is more affected by spatial effects, 3D inversion can control the validity of the pseudo-3D approach (Orfanos & Apostolopoulos, 2011). 3D surveys are useful in the creation of the amplitude and geometry of the complex resistivity anomalies (Bentley & Gharibi, 2004; Milkereit et al., 2008; Orfanos & Apostolopoulos, 2011; Mammo, 2013; Tavakoli et al., 2016a). Thus, the method can give correct position and the improved delineation of the target (White et al., 2001; Orfanos & Apostolopoulos, 2011; Moreira et al., 2012; Côrtes et al., 2016; Tavakoli et al., 2016b). Figure 6 and Figure 7 hold examples that show the effectiveness of 3D in sulfide explorations. 3Dinversion survey techniques provide high data acquisition rates, increase target resolution, offer a greater depth of penetration, and hence very cost-effective (White et al., 2001; Moreira et al., 2012; Côrtes et al., 2016; Tavakoli et al., 2016b).

The above images mainly contributed to better understanding the distribution of the sulfide mineralization around the mineralization zone. For example in Tavakoli et al.'s study, 3Dresistivity/IP was capable of providing a comprehensive overview of the electrical distribution in the upper ~450 m of the crust, which is of great importance for targeting VMS ore (Tavakoli et al., 2016b).

3D inversion is suitable for detecting electrical anisotropy while 1D and 2D were less pronounced (Meheni et al., 1996; Sretenovic & Arnaut, 2019). But, many facts need to be considered before choosing the method such as subsurface heterogeneity, background noise level, characteristics of an array, etc. Thus, multiple configurations are suggested to improve the reading of different subsoil features (Hesse, Jolivet, & Tabbagh, 1986; Côrtes et al., 2016).



Figure 6. Perspective view of 3D resistivity inversion (Milkereit et al., 2008).



Figure 7. 3D visualization of the electrical resistivity (a); chargeability (b) (Babaei et al., 2020).

4.2. Inversion Process for Sulfide Investigation

To obtain an accurate picture of the subsurface, it is necessary to carry out the pseudo section's inversion (Loke & Barkert, 1995). The inversion is performed by forward modeling operator by calculating theoretical data from input data and thereby calculating derivatives of the data with regard to the parameter (Pelton, Rijo, & Swift, 1978; Madsen et al., 2018). The massive sulfides deposits are indicated by the coincidence of high chargeability and low resistivity values after inversion (Moreira et al., 2012). It is noticeable that a suitable inversion method must simultaneously minimize the effects of data error and model parameter errors (Ja, Oo, & Arce, 2014). Therefore, to produce a better inversion, there should be re-run adjusting default parameters by manual selection of set-

tings such as vertical and horizontal weighting (Robertson & Hart, 2013). The "least-squares method" is the most method used amongst the papers analyzed in this review. The "least-squares method" seems to be the method that can successfully remove the distortions in the apparent resistivity pseudo section because it separates the electrode array geometry's effect on the apparent resistivity values from that which results from the subsurface resistivity (Loke & Barkert, 1995). It also separates overlapping anomalies caused by different bodies (Loke & Barkert, 1995).

5. Interpretation of Electrical Resistivity and IP Variation for Sulfide Ores and Their Host Rocks

5.1. Electrical Properties of Sulfide Host Rocks

The effectiveness of detecting sulfide deposits depends on the evolution of their hosting with adequate contrast in their physical properties between the base metals and their host rocks. Resistivity appears to be negatively correlated with porosity, Basalts indicate high resistivity and low IP along the resistivity, volcanic tuff areas are predominated by high resistivity values (Tavakoli et al., 2016b; Komori et al., 2017; Evrard et al., 2018) etc. The resistivity variation of various host rocks and sulfide minerals is summarized in Table 3.

Sulfide in a sedimentary host may be derived directly from the mantle or by reduction of sulfate either by a chemical or biological mechanism (Trudinger, 1981). Resistivity and chargeability of sulfide mineralization in sedimentary host

		10-2	10-1	10 ⁰	10 ¹	10 ²	10 ³	10 ⁴	10 ⁵
		Resistivity (Ω·m)							
	Soil								
Unconsolidated sediments	Clay								
	Sands and gravel							I	
	Shale								
Sedimentary rocks	Sandstone								
	Limestone								
	Granite								
Ignous metamorphic	Altered granite								
rocks	Basalt								
	Graphytic Schist								
	Pyrite								
Base metal sulfides	Pyrrhotite								
	Galena								
	Chalchopyrite								

Table 3. Electrical resistivities range sulfide minerals and host rocks.

(Ward, 1988; Telford, Geldart, & Sheriff, 1990b; Cardimona, 2002; Idornigie, Olorunfemi, & Omitogun, 2006).

expects to much contrast and detectable (Meju, 2002; Airo, 2015), because of their resistivity variations: Shale and clays present low values followed by sandstones with intermediate values, while coal and limestone beds have high values (Lau, 2000). Generally, sulfide in sedimentary hosts indicates low resistivity values with a strong correlation between the low resistivity and high chargeability areas for most of sedimentary host (Côrtes et al., 2016; Evrard et al., 2018). Massive sulfide surveyed around the submarine area usually shows low resistivity values lower than the seawater value (Goto et al., 2013; Komori et al., 2017; Ishizu et al., 2019). But, the sulfide hosted by quartz and carbonates leads to act as good electrical insulators with higher resistivity values (Katsube et al., 2003; Moreira et al., 2014; Côrtes et al., 2016; Han et al., 2016; Ishizu et al., 2019).

Seafloor massive sulfide (SMS) deposits are considered a high potential source of economic minerals s such as zinc, copper, tin, gold, and silver (Emsbo, 2007; Haroon et al., 2018). The electrical resistivity methods have revealed that SMS deposits exhibit a strong IP effect and lower resistivity than the surrounding host rock (Iijima & Sayanagi, 2013; Hördt et al., 2016; Ishizu et al., 2019). SMS area deposit indicates low resistivity values similar to or lower than the seawater (Ii-jima & Sayanagi, 2013).

Volcanogenic Massive Sulfide (VMS) deposits appear to have been formed by concentrations of base metal mineralizations by which their host rocks are dominated by submarine volcanic (Doyle & Allen, 2003; Iijima & Sayanagi, 2013; Ishizu et al., 2019). Most VMS deposits are classified based on metal content, tectonic context, or age (Barrie & Hannington, 1999; Doyle & Allen, 2003; Iijima & Sayanagi, 2013; Ishizu et al., 2019). VMS deposit may be characterized by a distinct zonation of the ore, gangue, and hydrothermally altered minerals. But, compared to sedimentary rock, igneous and metamorphic rocks present very high resistivity values (Lau, 2000; Airo, 2015). In the Iberian Pyrite belt, in Bathurst districts in Canada and Kuroko province of Japan, sulfide observed as volcano-sedimentary stratigraphic layers for being closely associated with volcanic lavas and pyroclastic rocks. They have formed a different relative participation of sedimentary/bacterio-genic and hydrothermal processes (Boulter, 1996; Barrie & Hannington, 1999; Sáez et al., 1999; Lentz & McCutcheon, 2006; Lentz, Thorne, & Beal, 2009; Walker, 2010; Piercey, Peter, & Herrington, 2015; Almod et al., 2019). VMS deposits (Sulfide in mafic or felsic hosted or occur as intercalation of basalts) are characterized by high electrical conductivity, high chargeability bordering zones, and sediments (such as graphitic shales) are more conductive than the associated volcanic host (Tavakoli et al., 2016b). However, the geochemical processes of weathering such as humidity, porosity, and hydrothermal alteration form clay can affect the target's resistivity. Also, major faults, fracture zones, and related structural control features in VMS prospects may be saturated with saline fluids, making them electrically conductive (Meju, 2002; Moreira et al., 2014; Tavakoli et al., 2016b). Though, when mineralized, they will be recognized by their elevated chargeability (Hawke & Brooker, 2001).

5.2. Electrical Resistivity and Chargeability of Sulfide Ores

Common sulfides except sphalerite, have high electrical conductivities (Wells, 1914; Ross, 1957; Meju, 2002; Pearce, Pattrick, & Vaughan, 2006; Aradis, Annigan, & Ewing, 2007; Airo, 2015) Resistivity and IP of Sulfide deposits depend very strongly on their quantity and the degree of connection between the various mineral grains or veins in the relevant host rock. When sulfide grains are isolated, they are not good electrical conductors because conductivity increases with the concentration of metallic particles (Revil, Florsch, & Mao, 2015). The ore bodies constituting more than 80% sulfide are considered as having "massive" texture; it is clear they are good electrical conductors (Langore et al., 1989). 20% up to 80% of the total volume is considered as "veinlet" texture. Due to electrical connections between the veinlets, such sulfide are also good electrical conductors (Langore et al., 1989). Sulfide content in the disseminated ore is 10% - 20% (Langore et al., 1989), because of the disseminated texture, sulfide is not good electrical conductors. It is also noted that the chargeability increase depending on the volumetric content of metallic particles (Scott & West, 1969; Revil, Florsch, & Mao, 2015).

The Pyrite and galena are frequently available as reasonably large single crystals. Simultaneously, chalcopyrite, pyrrhotite, and arsenopyrite occur in a compact, microcrystalline forms (Parasnis, 1956) massive sulfide vary in thickness from 2 to 10 cm, massive chalcopyrite layers vary in thickness from 2 to 5 mm (Tivey et al., 1995). Pyrrhotite laths are 20 to 30 μ m long, and 3 μ m wide and occur in interstices and intergrown with outer edges of chalcopyrite grain. Forty to 100 μ m clusters of sphalerite are intergrown with minor amounts of Pyrite (<10 μ m) (Tivey et al., 1995).

Pyrrhotite is highly conducive and can significantly influence a sulfide body's general electrical conductivity signature (Roach & Fitzpatrick, 2003). Pyrite and chalcopyrite also give potentials higher polarized (too conductive) state than galena (Wells, 1914; Roach & Fitzpatrick, 2003), but sphalerite is generally insultator with less conductivity and lower IP signatures than other sulfide minerals (Komori et al., 2017; Evrard et al., 2018). It can be conducive when associated with other conducive/chargeable sulfide minerals such as pyrite and pyrrhotite, even in small quantities (Roach & Fitzpatrick, 2003; Evrard et al., 2018). Even though (Hawke & Brooker, 2001)'s research showed that sphalerite is the primary mineral source of the induced polarisation effect observed in their investigated samples (Hawke & Brooker, 2001). It is also noted that Cu-bearing ores are likely to be more conductive but usually constitutes only a small part of the total sulfide volume in many deposits. Table 4 clearly describes the conductivities and chargeability of major sulfide minerals.

As mentioned in **Table 4**, the geophysical responses of massive sulfide usually dominated by low resistivity and high chargeability. It is not easy to make any conclusive deduction about exact resistivity and IP values for each type of sulfide.

Minouala	Resist	IP	
Willerais	Ω·m	Ω·m	ms
Pyrite	3×10^{-5} - 1.5	0.005 - 5	13.4
Chalcopyrite	$1.2 imes 10^{-5}$ - 0.3	0.01 - 0.07	9.4
Galena	3×10^{-5} - 300	0.003 - 0.03	3.7
Sphalerite	3.8×10^{11}		-
Pyrrhotite	-	0.001 - 0.005	~10
Arsenopyrite	-	0.03	-
Sulfides ore	10 - 50		

Table 4. Resistivity and chargeability of common sulfide minerals.

(Parasnis, 1956; Telford, Geldart, & Sheriff, 1990b; Pearce, Pattrick, & Vaughan, 2006; Airo, 2015; Evrard et al., 2018).

Different geological settings of the areas, make identical minerals to have different geophysical signatures or different minerals to produce the identical geophysical signature (Langore, Alikaj, & Gjovreku, 1989; Moreira et al., 2014; Côrtes et al., 2016). Some of the reviewed papers did not found differences between various sulfides, i.e., pyrite and chalcopyrite, in the spectral IP parameters with laboratory analysis (Langore, Alikaj, & Gjovreku, 1989). Also, mineralization may be of a chargeable nature because of the presence of other minerals which strongly associated with them like pyrite/marcasite (Côrtes et al., 2016; Evrard et al., 2018). Thus, minerals with high metallic conductivity even for disseminated sulfide ores, can have strong IP effects (Wang & Strangwayt, 1981). Though, the presence of graphite-bearing limestone, IP surveys is less useful for mapping sulfide mineralization (Guo, Dentith, & Zhao, 2000). But, graphite rarely occurs in massive sulfide. Table 5 presents examples of resistivity and IP methods in the exploration of sulfide deposits. It describes the types of surveys used, types of minerals and types of host rocks encountered, and shows their resistivity and IP responses.

6. Factors Affecting Exploration of Sulfides

Here are some factors that affect exploration of sulfide:

- ✓ The exploration of sulfides is potential sources of pollution, of the air and of surface waters and soils (Vaughan & Corkhill, 2017).
- ✓ The 1-D survey does not provide significant lateral changes, which may bring to gives inaccurate results or misleading results.
- ✓ When using 2D, the geological structures do not change in the direction perpendicular to the survey line, creating errors in interpretation.
- ✓ To delete negative IP data may cause the loss of essential information (Dahlin & Loke, 2015).
- ✓ Using large electrode spacing can mask data of thin layers (Mammo, 2013; Tavakoli et al., 2016b).

Date	Location	Types of mineral	Depth	Thick	Host rocks	Resistivity responses	Chargeability and IP effect of minerals	Dimensional survey
1981	Australia	pyrite	7 m	8 to 9 m	Volcanic rocks		30 ms, 4%	
1983	United state	Porphyry copper			Sedimentary	~75 Ω·m Laboratory	6%	
1989	Albania	sulfide Massive and disseminated	-	40 - 250	sediments	30 - 80 Ω·m	15 mV/V	1D
1995	Albania	pyrite and chalcopyrite Massive and disseminated			volcano-sedimentary rocks	<50 Ω·m	>20	2D
1997	Turkey	chalcopyrite-pyrite- sphalerite Disseminated			volcanic rock	0.6 to 2 Ω·m ~10 Ω·m Laboratory		2D
2000	China	pyrite, sphalerite and galena			schist and limestone	300 - 500 Ω·m Laboratory	≥12%	1D
2001	Australia.	sphalerite, pyrite and galena			The sediment hosted	16.8 - 760.8 Laboratory	10 - 25 msec	
2003	Australia	pyrite-chalcopyrite sphalerite, Massive			Volcanic Hosted	0.0002 - 0.8 Ω·m Laboratory	-	2D
2007	Canada	Zn-Pb-Ag deposit	82 m	<40 m	Volcanic and sedimentary hosted	<40 Ω·m		2D
2008	Nigeria Benue state	galena, sphalerite and pyrite	50 m		Sedimentary rocks	100 - 300 Ω·m	20 - 90 3 - 6 PFE	2D.
2013	Japan	Submarine massive sulfide (SMS)			Hydrothermal chimneys.	≤0.3 Ω·m		2D
2012	BLAZIL	Oxides and sulfide			quartz, clay and schists	<20 Ω·m	>30 ms	
2013	Ethiopia	chalcopyrite, sphalerite, pyrite, pyrrhotite			Volcanic hosted	<500	>40 ms	2D & 3D
2016	BLAZIL	copper-porphyry Cu disseminated	below 50 m - 80 m		In sediments	Less than 20 Ω·m		2D
2014	Nigeria	galena, sphalerite and pyrite	50 m	30 m	barite and gypsum	100 - 300 Ω·m		2D
2016	sweden	pyrite, sphalerite, chalcopyrite, and arsenopyrite	≈1-km depth		metasedimentary rocks and volcanic rocks	Depends on the site 2 k Ω·m - 4 k Ω·m; 6 k Ω·m - 10 k Ω·m	≤27 mV/V - 70 mV/V	2 & 3D

Table 5. Examples of resistivity and IP methods in the exploration of sulfide deposits.

2016	South Korea	Au-Ag deposits			the solidification (quartz veins) exposed in outcrop	< 600 Ω·m	>2.7 mV·V ⁻¹ - 3 mV·V ⁻¹	2D & 3D
2016	Indian	Ni-Cu-PGE ores and base metal sulfide deposits (chalcocite, chalcopyrite or pyrite minerals)	-55 m to 74 m -320 m and 480 m -55m to 74m		mafic-ultramafic	1) 200 - 1500 Ω·m 2) 1500 - 11,000 Ω·m 3) 1580 - 10,000 Ω·m	Depends on the site but the lowest: ~20 mV/V Highest 54 mV/V	2D
2016	Iran	pyrite, sphalerite, and galena	-	-	-	<200 Ω·m.	≥30 ms	2D
2018	South Sulawesi	pyrite			Sedimentary host	≤50 Ω·m	≥3%	2D & 3D
2018	Belgium	Pb-Zn (sphalerite, with galena and pyrite)			sedimentary host rock	<80 Ω·m	>0.1 mV/V	2D
2019	Japan	Copper, lead, and zinc	40 m		seafloor massive sulfi	<0.2 Ω·m		2D
2019	Canada	Ni-Cu-PGE deposit	beneath the 45 m		volcanic rocks		>25 mV/V	
2020	Iran	disseminated nature Porphyry Cu Mineralization		80 m	Volcanic tuff	500 Ω·m	50 ms	2D & 3D

Continued

- ✓ Interference from grounded structures such as pipelines, power lines, and fences can distort the signals (Sternberg, 2002).
- ✓ Sometimes pyrite in fine-grained sediments such as mudstones and shales may produce false anomalies (Sternberg, 2002).
- ✓ In the interpretation of resistivity data, the author should emphasize the fact that there are other causes of low resistivity other than sulfides and explain how to constrain the interpretation to be unique to sulfides.

7. Conclusion

It is much known about resistivity and IP surveys in mineral exploration. These methods are simple, fast, cheap, and effective for sulfide mineral exploration. The reviewed papers showed that these methods have been successfully used in sulfide exploration whereby many results showed that low resistivity correlates with high chargeability and vice versa. This review is the wealth of resistivity and IP properties exhibited by sulfide minerals and their host. This review covered different distinct techniques of investigation to make the reader understand the procedures and appropriate methods that can be applied in mining exploration by showing the success and problems affecting exploration. This research could be useful as a guide for the future geophysical studies such as geophysics, mineralogy or in mineral exploration. However, many authors did not give the values

attributed to each type of minerals but the range value. Some failed to include the area covered during their survey. It could be suggested therefore to present the area covered during the geophysical survey or give the number of traverse and line with their space interval from which interested readers can get the idea of the area covered for future research.

Acknowledgements

This research study is supported by Hohai University.

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I solemnly declare that this manuscript is the collection of original research data and does not contain any copied contents from other sources. Proper citations of previous works were made and to the best of our knowledge.

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Availability of Data and Material

All the data and materials used are available.

Authors' Contributions

All the authors contributed significantly to writing this article. The authors read and approved the final manuscript.

Conflicts of Interest

The authors declare that there is no competition of financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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