

Electrical Resistivity and Induced Polarization Data Correlation with Conductivity for Iron Ore Exploration

Andy A. Bery

*Geophysics Section, School of Physics, Universiti Sains Malaysia, 11800 Penang
Corresponding author e-mail: andersonbery@yahoo.com.my*

Rosli Saad

Geophysics Section, School of Physics, Universiti Sains Malaysia, 11800 Penang

Edy Tonnizam Mohamad

*Faculty of Civil Engineering, Department of Geotechnics and Transportation,
Universiti Teknologi Malaysia*

Mark Jinmin

Geophysics Section, School of Physics, Universiti Sains Malaysia, 11800 Penang

I.N. Azwin

Geophysics Section, School of Physics, Universiti Sains Malaysia, 11800 Penang

Norsalkini Mohd Akip Tan

*Faculty of Civil Engineering, Department of Geotechnics and Transportation,
Universiti Teknologi Malaysia*

M.M. Nordiana

Geophysics Section, School of Physics, Universiti Sains Malaysia, 11800 Penang

ABSTRACT

A DC electrical resistivity and Time Domain Induced Polarization (TDIP) survey and on-site test were undertaken at an iron ore exploration area site in Pagoh, Malaysia for the purpose of imaging the possible area for mineral exploration. Two geophysical survey lines were conducted to identify and make possible to enhance the resolution of subsurface structure when compare to resistivity surveys alone. These two resistivity and induced polarization survey lines were carried out crossing the iron ore area giving a dense coverage over the area. The results show that it is possible to both resolve the geological structure using electrical resistivity and induce polarization method. In particular, it is possible to find the iron ore (hematite) which also correlates with the geostatistical analysis obtained from two data sets of survey lines and assisted with the on-site sampling test. The interpretation of the geophysical imaging finding was constrained by the on-site sampling test results. The results show that the on-site test and survey are successful in giving a valid and reliable infield data in producing iron ore for marketing purpose. The results from infield survey model and geostatistical analysis are discussed here supporting by the successful iron ore exploration of the study area which is for economic important in mining and industrial purposes.

KEYWORDS: Electrical Resistivity; Induced Polarization; Geostatistical; Iron Ore Exploration

INTRODUCTION

Mining exploration was very active during the first decade of the twenty-first century because there were numerous advances in the science and technology that geophysicists were used for mineral exploration. Most geophysical techniques have as their origin the oil and mining industries. In such industries the primary need of a developer is to identify the locations of minerals for exploitation, against a background of relatively large financial rewards once such deposits are found.

All geophysical techniques are based on the detection of contrasts in different physical properties of materials. Electrical methods depend on the contrasts in electrical resistivity (Telford *et al.*, 1990). Electric resistivity surveying along the earth's surface is a well-known geophysical exploration technique (Bery and Saad, 2012a). Due to its conceptual simplicity, low equipment cost and ease of use, the method is routinely used in mineral exploration. Two techniques that were conducted in this study area were electrical resistivity and induced polarization (IP) method. Electrical resistivity surveys are used to provide information on the depth to bedrock and information on the electrical properties of bedrock and overlying units. The IP method makes use of the capacitive action of the subsurface to locate zones where clay and conductive minerals are disseminated within their host rock.

In several studies, significant using electrical resistivity has been used for mineral exploration using cross-borehole electric methods in ore body delineation (Qian *et al.*, 2007). They have successfully imaged the massive sulphide mineralization in a moderately conductive host. Badmus and Olatinsu (2009) have carried out 62 vertical electrical sounding (VES) to map limestone deposits. Their research work further showed that the occurrence of vast deposit of limestone, which can be of economic important in mining and industrial purposes.

Recently, Son *et al.*, (2011) has used tomography surveys method for mineral exploration. They have used complex resistivity method called spectral induced polarization. Sodeifi and Hafini, (2001) has used induced polarization method in polymetal mines exploration for polymetal bodies. They used suitable array in their study for proposed drill holes at the polymetal mines. Electrical property contrast between ore bodies and country rocks, at initial exploration stage, resistivity-central gradient array, induced polarization-central gradient array and induced polarization-sounding survey were conducted by (Li *et al.*, 2009). They used induced polarization method in exploration of the Baizhangzi Gold Deposit in Liaoming and the electrical anomalies were drill tested which intersected significant mineralization. Yu *et al.*, (2007) have implemented experiments on the known gobs in the Jiayuan Coal Corporation in Qinyuan of Shanxi using the method of dual frequency induced polarization. Through reorganizing and analyzing the data, they got that higher apparent resistivity rate and lower apparent amplitude-frequency rate exist in the gob without water by detection and the position of the gob underground was precisely given. Induced polarization (IP) measurements were also conducted by (Slater *et al.*, 2006) on saturated kaolinite-, iron-, and magnetite-sand mixtures as a function of varying percentage weight of a mineral constituent: 0 – 100 % for iron and magnetite and 0 – 32 % for kaolinite. They determined the specific surface area for each mineral using nitrogen gas adsorption, where the porosity of each mixture was calculated from weight loss after drying.

In this study we examined the applicability of DC electrical resistivity and time-domain induced polarization (TDIP) surveys of the subsurface to discrimination of lithogenic contributions in area characterised by good potential area for iron are exploration. It is of great important to show the empirical correlation (associative statistical) of physical parameters for induced polarization (IP) and resistivity from infield survey and on-site sampling test. Both methods were analysis to reach the objectives of this study. The objective of this study is determining correlation between electrical

parameters (chargeability, resistivity and conductivity) of survey model. Second objective is to determine correlation of on-site test results for induced polarization and resistivity imaging parameters were done to understand the characteristic of the subsurface in producing iron ores for economic and mining purpose. In this paper, we presented the results of electrical resistivity and induced polarization methods to determine the distribution of iron ore in Pagoh, Johor, Malaysia.

GEOLOGY SETTING, MATERIALS AND METHODS

Geology area

Generally the area is covered by alluvium of Jurassic-Triassic age with arenaceous and argillaceous beds predominate. There is granitic intrusion of Upper Carboniferous age nearby the studied area (**Map 1**). As reported by Bean (1969), most of iron mines in Malaysia are Permian-Triassic age, and this area has a similar age of other iron deposit elsewhere. Commonly, the ore bodies found in Malaysia are featured by the strong supergene enrichment by tropical weathering process.

DC Electrical Resistivity and Time-Domain Induced Polarization Method

The purpose of resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. The true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as mineral and fluid content, porosity and degree of water saturation in the rock (Bery and Saad, 2012b). Variations in electrical resistivity may indicate changes in composition, layer or contaminant levels. Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigation. More recently, this resistivity method has been used for environmental surveys (Bery and Saad, 2012c).

The fundamental physical law used in resistivity surveys is Ohm's Law that govern the flow of current in the ground. The equation for Ohm's Law in vector for current flow in a continuous medium is given by Equation (1) below.

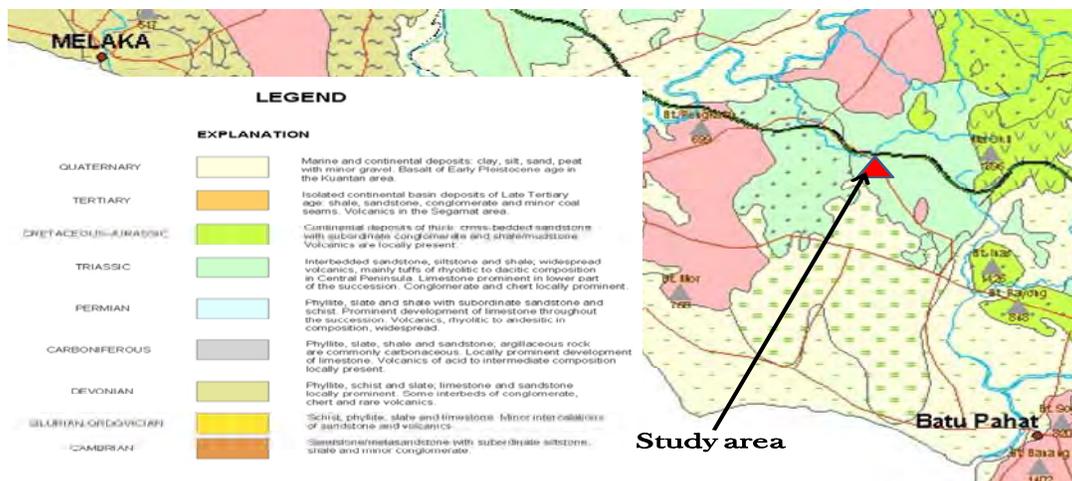
$$\vec{J} = \vec{\sigma}\vec{E} \quad (1)$$

where $\vec{\sigma}$ is the conductivity of the medium, \vec{J} is the current density and \vec{E} is the electrical field intensity. In practice, what is measured is the electrical field potential. We note that in geophysical surveys, the medium resistivity $\vec{\rho}$, which is equals to the reciprocal of the conductivity ($\vec{\rho} = 1/\vec{\sigma}$).

In the time-domain method, the residual voltage after the current cut-off is measured. Some instruments measure the amplitude of the residual voltage at discrete time intervals after the current cut-off. A common method is to integrate the voltage electronically, V_s for a standard time interval. In the Newmont $M_{(331)}$ standard (VanVoorhis *et al.*, 1973), the chargeability, m_t is defined as Equation (2).

$$m_t = 1870 \frac{\int_{0.15}^{1.1} V_s dt}{V_{DC}} \quad (2)$$

where the integration is carried out from 0.15 to 1.1 seconds after the current cut-off and V_{DC} is direct current voltage. The chargeability value is given in milliseconds (msec). The chargeability value obtained by this method is calibrated (Summer, 1976) so that the chargeability value in msec has the same numerical value as the chargeability given in mV/V. In theory, the chargeability in mV/V has a maximum possible value of 1000 (Loke, 2001).



Map 1: Geological map of the study area (Source: Jabatan Mineral dan Galian, Malaysia)

Materials and Methods Applied

Beside than infield survey at the study area, we were also conducted on-site tests which consisted of electrical and magnetic susceptibility test for selected samples. The selected samples were decided base on different colour and depth. The reason for this sampling method chosen was the different soil's colour represent the different geological process undergoes in the sample. Besides that, it also governs by different mineral present in the soil at various depths. The equipments used were shows as **Figure 1** below.



Figure 1: Induced polarization (IP) tester meter (left) and IP survey used in this study (right)

For induced polarization (IP) test, 10 of stacks, signal time with 2 second and arithmetic mode are chosen parameters. Beside than that, soil-plate contact dimension is fixed with 3750 mm^2 as contact area and 300 mm as contact length (**Figure 1**). Meanwhile, transmitting parameters are selected in this study with constant current of $500 \mu\text{A}$ and voltage of 3 V, 6 V, 9 V and 12 V. For each tested soil samples, an average of resistivity and chargeability using these 4 different voltages with constant current is recorded for detailed analysis. This method used for on-site chargeability test is called two electrodes induced polarization test.

The equipments used for infield induced polarization survey is 2 cables rolls, Terrameter SAS4000, Electrode Selector ES10-64, connection cable (SAS4000 to ES10-64), 12 V battery, 41 non-polarized electrodes, 42 jumper clips, compass and GPS.

RESULTS AND DISCUSSION

The raw data from induced polarization survey is processed using RES2DINV software. Then each data set was analysed using statistical for their model agreement. Meanwhile, on-site test results were calculated and analyse using statistical distribution parameters of chargeability and resistivity values were for all soils. Both methods in this study used the data sets collected from the study site (iron ore exploration) and non soil samples collect for other analysis (laboratory) because we wanted do correlation base on soil's actual condition of their deposition. This will able to assist us to understand characteristics of subsurface for producing iron ores in this study area.

The model of resistivity and induced polarization values are applied with the smoothness-constrained inversion which presented in **Figure 2** and **Figure 3**. This formulation is given by Equation (3).

$$(\bar{J}^T \bar{J} + \lambda \bar{F}) \Delta \bar{q} = \bar{J}^T \bar{g} - \lambda \bar{F} \bar{q} \quad (3)$$

Here parameter of $\Delta\vec{q}$ is the model parameter change vector, $\vec{J}^T \vec{J}$ is the Jacobian matrix (of size m by n) of partial derivatives, The matrix product $\vec{J}^T \vec{J} \vec{J} \vec{J}^T$ is nearly singular, $\vec{\lambda}$ is known as the damping factor, \vec{g} is known as discrepancy vector and \vec{F} given by

$$\vec{F} = \alpha_x C_x^T C_x + \alpha_y C_y^T C_y + \alpha_z C_z^T C_z \tag{4}$$

and C_x , C_y and C_z are the smoothing matrices in the x-, y- and z-directions. α_x , α_y and α_z are the relative weight given to the smoothness filters in x-, y- and z-directions.

Because of the relevance of the chargeability parameter M_0 for depicting iron ore areas as shown (Nordiana *et al.*, 2012), it was chosen in this paragraph to show the results from chargeability parameter. Here, the interpretation of the geophysical results are made base on the physical and geological aspects. Within the iron ore exploration, the resistivity and chargeability model can be divided into two layers. The first layer on top with 4 to 5 m thickness from surface can be classified as mixes of alluvium hard layer with boulders with resistivity range value of 15 to 250 $\Omega.m$ and chargeability range value of 5.0 to 30.0 msec. The second layer bottom is below 5 m from the surface has resistivity range value of 500 to 2500 $\Omega.m$ and chargeability range value of 0.1 to 1.0 msec. These physical values range shows that the ore can be classified as soil-hematite material.

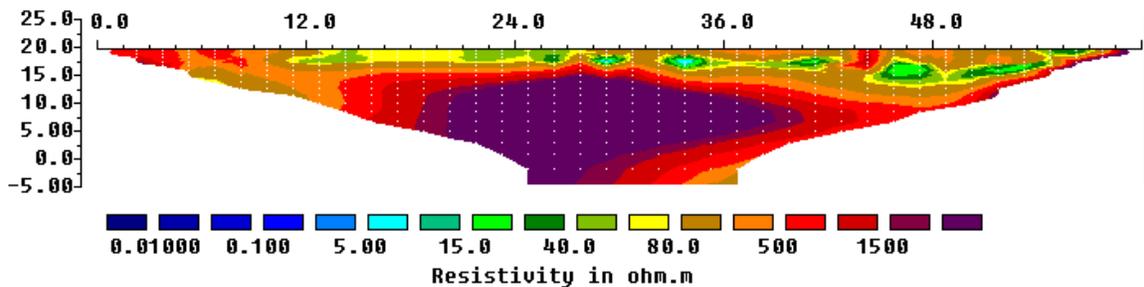


Figure 2: Resistivity model with topography for LINE 01.

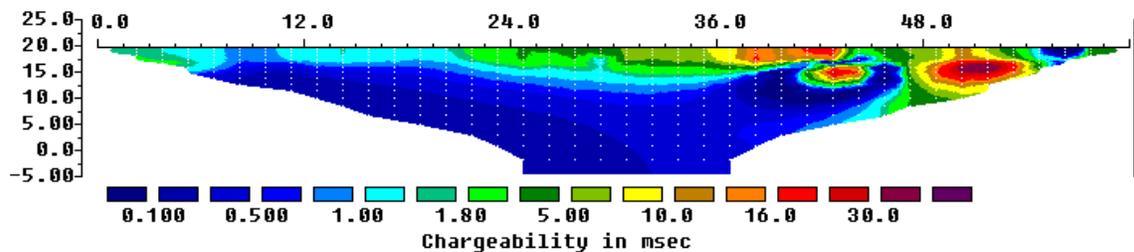


Figure 3: Induced polarization model with topography for LINE 01.

The model of resistivity and induced polarization values are also applied with the smoothness-constrained inversion which are shown in **Figure 4** and **Figure 5**. Based on the results obtained, the resistivity and chargeability model for LINE 02 also can be divided into two layers. The first layer on top is 4 to 7 m thickness of alluvium hard layer, with resistivity range value of 15 to 250 $\Omega.m$ and chargeability range value of 1 to 1.8 msec. Meanwhile the second layer with resistivity range value of

500 to 2500 Ω .m. However, the chargeability value of this model section is quite low and similar to section model LINE 01. The reason for this situation is caused by the distribution of hematite at subsurface is nearly random and it also mixes with soil (alluvium) underneath of LINE 02. This is supported by the chargeability range value for this portion is also within 0.1 to 1.0 msec. The judgment for this interpretation made base on chargeability value of hematite has lower values compares to alluvium values and hematite classified as oxides material compared to alluvium.

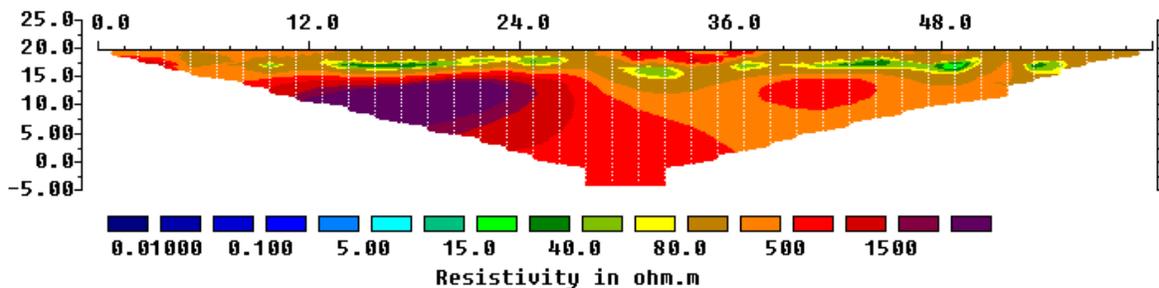


Figure 4: Resistivity model with topography for LINE 02.

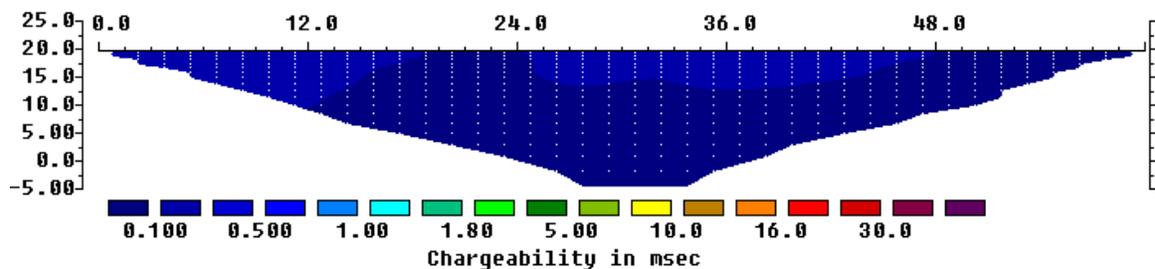


Figure 5: Induced polarization model with topography for LINE 05.

The model of conductivity is obtained from the smoothness-constrained inversion is shown in **Figure 6** and **Figure 7**. The data sets were inverted into models of conductivity of both survey lines using Surfer 8 software. These two results show that the both line have two different conductivity portions in the subsurface. The conductivity obtained from LINE 01 has conductivity range value from 0.000194 to 0.0692 S/m. Meanwhile conductivity obtained from LINE 02 has conductivity range value from 0.000461 to 0.052 S/m. In this case, we observe a reasonable agreement with both resistivity models (**Figure 2** and **Figure 4**) above. The negative values appeared at the contour value next to the model is the interpolation data point effect. However, our consideration is only inside section (trapezium) which is similar to the resistivity model because the negative contour did not have any real data points.

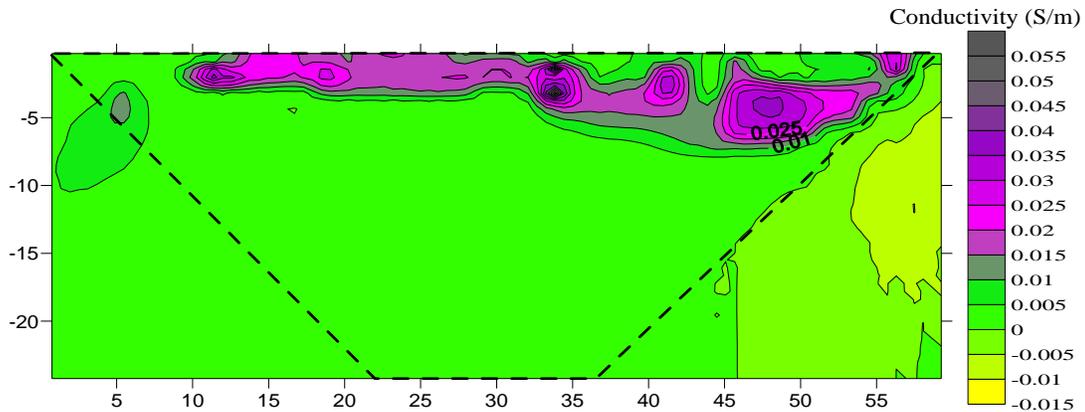


Figure 6: Conductivity model with topography of LINE 01 of study area

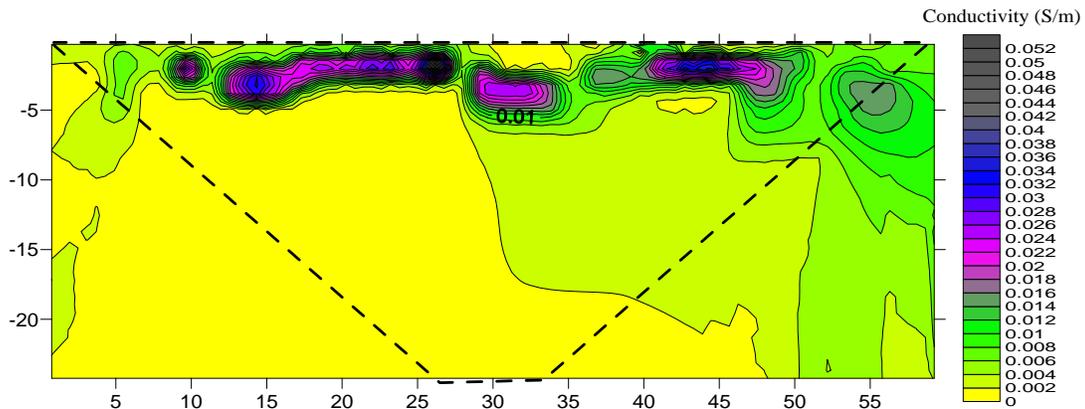


Figure 7: Conductivity model with topography of LINE 02 of study area

In this study, we were also carried out geostatistical analysis is to provide meaning to what otherwise to be a collection of numbers and/or values. The meaningfulness of data derives from the clarity with which one specifies the problem or question being addressed and the precision with which pertinent information is gathered.

Based on our geostatistical analysis in this second approach, we are able to determine the characteristic of the subsurface parameters of the iron ore exploration area. The empirical correlation between conductivity and resistivity for LINE 01 is $\sigma = 0.0086e^{-0.0009(\rho)}$ with regression coefficient (R^2) at approximately 0.8074 (**Figure 8**). Meanwhile empirical correlation for LINE 02 is $\sigma = 0.0091e^{-0.002(\rho)}$ with regression coefficient (R^2) at approximately 0.7852 (**Figure 9**). This correlation shows that electrical conductivity is the reciprocal (or inverse) of electrical resistivity. The empirical correlation between chargeability with resistivity for LINE 01 is $M = -0.388 \ln(\rho) + 5.0385$ with regression coefficient (R^2) at approximately 0.1388 (**Figure 10**). Meanwhile, empirical correlation for LINE 02 is $M = 0.0806e^{0.0001(\rho)}$ with regression coefficient (R^2) at approximately 0.0113 (**Figure 11**) as shown below.

In this section, we show the result of on-site sampling test. The on-site sampling points in this study were chosen base on their different depth and also colour. The geometry of the on-site sampling discussed in previous section. The empirical correlation between chargeability with resistivity is $M = -0.3802(\rho) + 108.63$ with regression coefficient (R^2) at approximately 0.3382 (Figure 12).

In this study we are also did univariate statistical analysis that is methods for analyzing data sets on a single variable. This method is used in this geostatistics analysis to distinguish a distribution of geophysical parameters (Resistivity, Chargeability and Conductivity) obtained in this study.

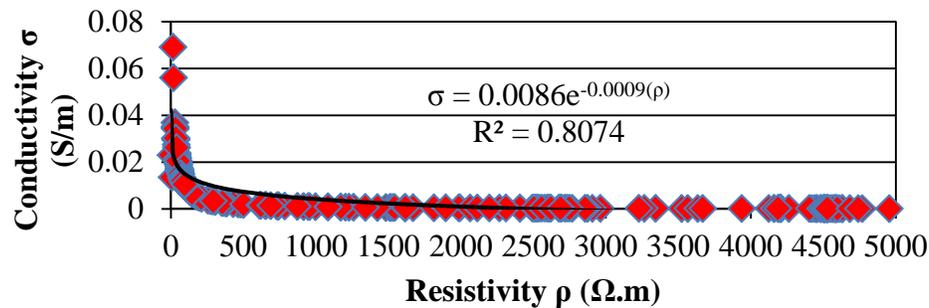


Figure 8: Empirical correlation of electrical conductivity and resistivity of LINE 01 subsurface

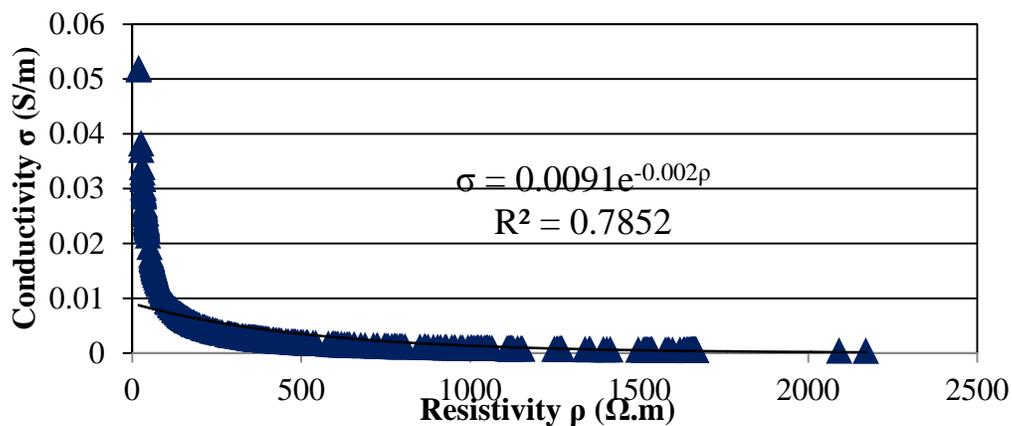


Figure 9: Empirical correlation of electrical conductivity and resistivity of LINE 01 subsurface

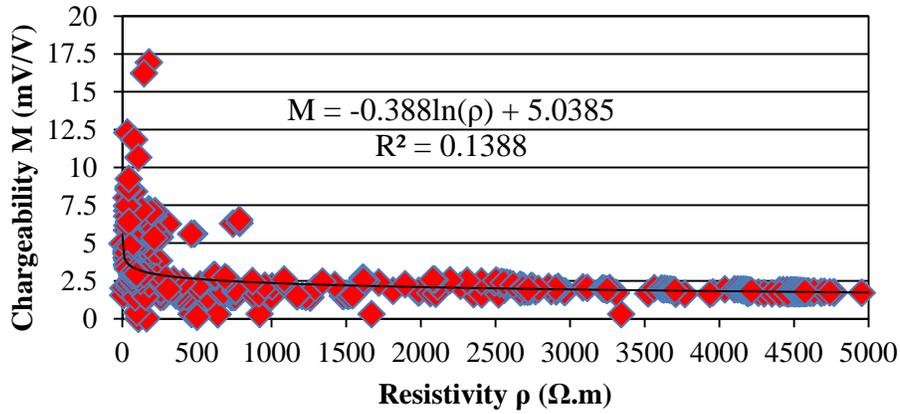


Figure 10: Empirical correlation of chargeability with resistivity of LINE 01 subsurface

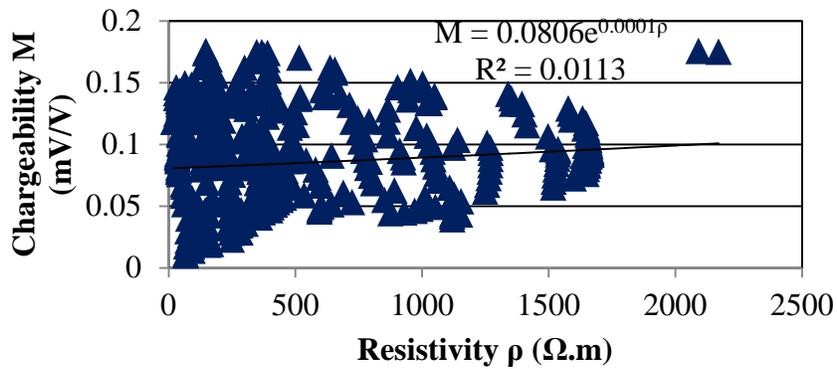


Figure 11: Empirical correlation of chargeability with resistivity of LINE 02 subsurface

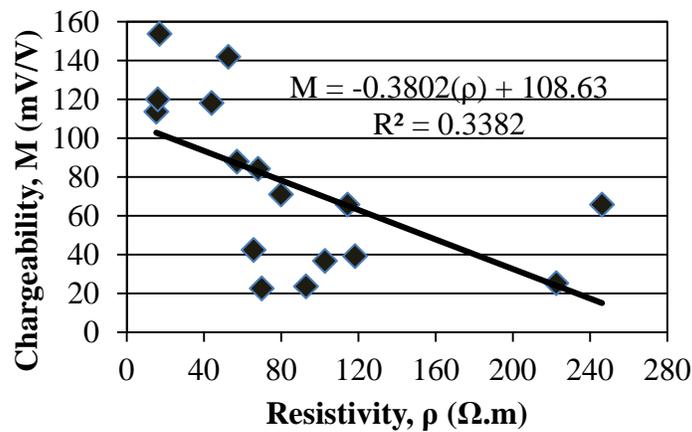


Figure 12: Correlation of chargeability and resistivity for on-site test

Table 1: Univariate statistical analysis result for LINE 1 infield survey

Parameters	Conductivity (S/m)	Resistivity (Ω .m)	Chargeability (mV/V)
Minimum	0.000194	0.24	0
25%-tile	0.000324	75.64	1.74
Median	0.001534	653.48	1.93
75%-tile	0.01280	3046.7	2.56
Maximum	0.06920	5164.8	16.94
Midrange	0.034697	2582.52	8.47
Range	0.069006	5164.56	16.94
Mean	0.007193	1604.04	2.6354
Trim Mean (10%)	0.006064	1524.60	2.3904
Standard Deviation	0.009952	1751.32	1.9383
Variance	9.91E-05	3067151	3.7570
Coefficient of Variation	1.383626	1.091819	0.7354
Coefficient of Skewness	1.807064	0.677953	3.1719

Table 2: Univariate statistical analysis result for LINE 2 infield survey

Parameters	Conductivity (S/m)	Resistivity (Ω .m)	Chargeability (mV/V)
Minimum	0.000461	19.24	0.0103
25%-tile	0.001155	147.25	0.0652
Median	0.00279	358.57	0.094
75%-tile	0.006791	865.54	0.1294
Maximum	0.052	2170.6	0.1759
Midrange	0.026230	1094.92	0.0931
Range	0.051539	2151.36	0.1656
Mean	0.006201	548.160	0.09533
Trim Mean (10%)	0.00512	514.092	0.0954
Standard Deviation	0.00809	534.147	0.0389
Variance	6.56E-05	285314	0.0015
Coefficient of Variation	1.3054	0.97443	0.4088
Coefficient of Skewness	2.3594	1.0927	-0.0447

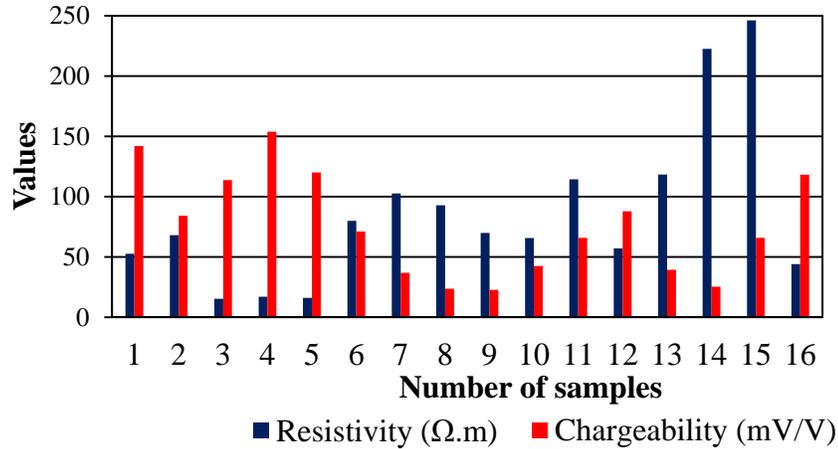


Figure 13: Histograms of samples number with respect to their resistivity and chargeability value for on-site test

For the purpose of further information of on-site sampling test, we have carried out geostatistical mathematic of all the collected results. There we used mean, variance and standard deviation as our mathematical parameters. In statistics, standard deviation shows how much variation or dispersion exists from the average (mean or expected value). The values for each sampling test are shown in **Figure 13**. The results for the on-site sampling test are Mean is 86.395859 $\Omega.m$ and 75.778703 mV/V. Variance is 4114.729929 ($\Omega.m$)² and 1758.972826 (mV/V)². Meanwhile, standard deviation is 64.146161 $\Omega.m$ and 41.940110 mV/V. The summary for these statistical is shown in **Table 2**.

Based on **Table 2**, the standard deviation indicates that the data points tend to be close to the mean. The results above showed that the on-site test and supported by survey results are successful in giving preliminary and reliable infield information in producing iron ore at the study area for marketing purpose. The result discussed here was leading by the successful iron ore exploration of the study area. The iron ore exploration have successfully produced 20 000 tonne of iron ore by exploration area of 1.5 ache. The **Figure 14** and **Figure 15** below shows the iron ore exploration area and the iron ore produced from the geophysical study area.

Table 3: Statistical analysis results for the on-site sampling test

Parameters	Resistivity, ρ	Chargeability, M
Mean	86.4	75.78
Variance: σ^2	4114.7	1758.97
Standard Deviation: σ	64.146	41.94



Figure 14: The area view where geophysical surveys were conducted at iron ore exploration (Left) and iron ore (hematite) is accumulated nearby the iron ore exploration area (Right)

CONCLUSION

The geophysical survey together with the on-site sampling test used in this study was successfully allowed the recognition of physical parameters important for economic important in mining and industrial purposes. In particular it was possible to identify the subsurface material using this integration of survey and on-site test of geophysical methods. Beside than provide low cost of subsurface investigation, the most important criteria is the results obtained in this study provided reliable results for more possible area for iron ore exploration. It is important to conduct this research in terms of infield work because it can help members to join the geophysical community (engineers and architects) to improve understanding of the obtained geophysical results. In addition, the imaging (models) and geostatistical analysis methods applied in this study was able to increase the validity and reliability of results in the field of geophysical imaging subsurface.

ACKNOWLEDGEMENT

I would like to wish thanks to USM Laboratory Assistants Mr. Shahil Ahmad Khosaini and Mr. Azmi Abdullah helping in data acquisition for this study. I also wish to thank anonymous reviewers for insightful comments that helped improved the quality of the manuscript.

REFERENCES

1. A. Bery and R. Saad, (2012a) "Clayey Sand Soil's Behaviour Analysis and Imaging Subsurface Structure via Engineering Characterizations and Integrated Geophysical Tomography Modeling Methods," *International Journal of Geosciences*, 3(1), 93-104. doi: 10.4236/ijg.2012.31011.
2. A. Bery and R. Saad, (2012b) "Tropical Clayey Sand Soil's Behaviour Analysis and Its Empirical Correlations via Geophysics Electrical Resistivity Method and Engineering Soil Characterizations," *International Journal of Geosciences*, 3(1), 111-116. doi: 10.4236/ijg.2012.31013.
3. A. Bery and R. Saad, (2012c) "Correlation of Seismic P-Wave Velocities with Engineering Parameters (N Value and Rock Quality) for Tropical Environmental Study," *International Journal of Geosciences*, 3(4), 749-757. doi: 10.4236/ijg.2012.34075.

4. Badmus B.S. and Olatinsu O.B., (2009) "Goelectrical mapping and characterization of limestone deposits of Ewekoro Formation Southwestern Nigeria," *Journal of Geology and Mining Research*, 1(1), 008–018.
5. Bean J.H., (1969) "The iron-ore deposits of WEST Malaysia," *Geological Survey of Malaysia Economic Bulletin*, 2.
6. Li X., Zhi F., Ma J.D., Ang Z.W., Ao Y.F., Jiang Z.H., Fu Q., Song X.J., Yuan G.P., Xuan L., Zhang D.H., Guan C.J. and Wang H., (2009) "The application and significance of the induced polarization method in exploration of the Baizhang Gold Deposit in Liaoning," *Geology and Exploration*, 2.
7. Loke M.H., (2001) "Tutorial: 2-D and 3-D electrical imaging surveys," 1-129.
8. Nordiana M.M, Saad R., I.N Azwin and Mohamad E.T., (2012) "Iron ore detection using electrical methods with enhancing resolution (EHR) technique," *National Geoscience Conference*, Sarawak, 65-66.
9. Qian W., Milereit B. and Graber M., (2007) "Borehole resistivity tomography for mineral exploration," EAGE 69th Conference and Exhibition, London, UK.
10. Slater L., Ntarlagiannis D. And Wishart D., (2006) "On the relationship between induced polarization and surface area in metal-sand and clay-sand mixtures," *Geophysics*, 71(2) A1-A5.
11. Sodeifi A.H. and Hafini M.K. (2011) "The application of Induced polarization polymetal mines," *Exploration Journal of the Earth*, (Abstract).
12. Son J., Park S. and Kim J., (2011) "Tomographic surveys for mineral exploration using complex resistivity method," American Geophysical Union, Fall Meeting, Abstract#NS52B-1757.
13. Sumner J.S., (1976) "Principles of induced polarization for geophysical exploration," Elsevier Scientific Publishing Company.
14. Telford W.M., Geldart L.P. and Sheriff R.E., (1990) "Applied Geophysics," (Second Edition), Cambridge University Press.
15. Van Voorhis G.D., Nelson P.H. and Drake T.L., (1973) "Complex resistivity spectra of porphyry copper mineralization," *Geophysics*, 38(1) 49-60.
16. Yu C.T., Liu H.F. and Gao J.P., (2007) "The experimental study on the dual frequency induced polarization method detecting coal mine gob," *Progress in Geophysics*.

