The electrical complex impedance measurement of rock samples using simple method on Halmahera rock samples

G Handayani and M H K Usman

1Laboratory of Earth Physics Bandung Institute of Technology

E-mail: gunawanhandayani@gmail.com

Abstract. The electrical complex impedance is very important physical parameter to determine the fluid and matrix condition of the rock sample. One mechanism in the samples that influences this complex, frequency – dependent behaviour of resistivity is the disseminated metal ores which can block the pores and subsequently trigger the mechanism for storage/delay. Pore water ions build up on either side of the grain, results in the effect of a capacitor. This paper presents a simple experimental set up to measure the complex resistivity of rock samples. The main mechanism is generation of high voltage sinusoidal signal. This is implemented as collector voltage of a transistor. The high voltage sinusoidal signal then is applied on either side of the rock sample. At two distances of the sample we measure the resulting voltage using the oscilloscope. The observed delay can be considered as the measured phase, whereas the amplitude of the observed voltage is considered as the voltage. We determine the absolute impedance as the voltage divided by the current. Using this simple method we measured the complex impedances of 14 rock samples obtained from Halmahera Island. From the results of measurement, we tried to infer and to model the disseminated metal ores of the samples.

1. Introduction

The electrical complex impedance is very important physical parameter to determine the fluid and matrix condition of the rock sample. One mechanism in the samples that influences this complex, frequency – dependent behavior of resistivity, is the disseminated metal ores which can block the pores and subsequently trigger the mechanism for storage/delay. This phenomenon is called Electrode polarization. It occurs when metallic minerals are present in a rock. The electrical current is conducted through the metallic grains and by means of ion movement of the fluid in the pores as described in Figure 1.

![Figure 1. Mechanism of complex resistivity: electrode polarization.](image-url)
When the voltage is applied at two points on the rock, the electronic conduction through the metallic grain is very fast, whereas at the interface the rate of electronic exchange between ions and metallic grains is slow, as the results there is a build-up of charge in the boundary between metallic grains and pore fluids. When the voltage is removed, the accumulation of charges diffuses back to the original location and causes a time-delayed decaying voltage. This phenomenon is called electrode polarization or overvoltage which causes inductor effect on electronic circuit (Fu, H, 2013) (Sumner, J.S., 1976).

There are three ways electrical current can flow through the rock i.e.: 1) Electronic conduction (Ohmic) 2) Electrolytic conduction (through ionic movement) 3) Dielectric conduction (electrode polarization mechanism).

2. Methodology

The principle of complex resistivity measurement on the rock samples can described as in Figure 2.

![Figure 2. The principle of complex resistivity measurement on the rock sample.](image)

Referring to Figure 2, the resistance R of the rock sample is governed by the following formula:

\[ R = \rho \frac{L}{A} \]  

(1)

where R is resistance, \( \rho \) is resistivity, L is sample length and A is area of the sample.

![Figure 3. Equivalence circuit of complex resistivity of rock samples.](image)

The complex resistivity measurement of the rock sample can be diagrammed by the circuit in Figure 3. In complex resistivity measurement, the rock sample can be considered as the resistor, capacitor and inductor in parallel circuit. If the AC voltage source \( V(t) = V_o \sin \omega t \), the total current would be the sums of three currents that passing through the resistor, inductor and capacitor i.e.:

\[ I(t) = I_R(t) + I_L(t) + I_C(t) = I_{R0} \sin \omega t + I_{L0} \sin (\omega t - \frac{\pi}{2}) + I_{C0} \sin (\omega t + \frac{\pi}{2}) \]  

(2)

The electric current through capacitor \( I_{C0} \), inductor \( I_{L0} \), and resistor \( I_{R0} \) of Figure 3, along with the applied potential \( V_o \), follows the phasor diagram in Figure 4 (Halliday, Resnick, 2007).
Figure 4. Phasor diagram of the parallel circuit.

And \( I_0 = \frac{V_0}{Z} \), \( Z = \frac{V_0}{I_0} \); or \( Z = \frac{V_{rms}}{I_{rms}} \); \( \phi \) is the phase difference between \( V_0(t) \) and \( I_0(t) \).

Figure 5. Diagram of complex impedance \( \vec{Z} \).

The complex impedance (Figure 5) can be calculated as:

\[
\frac{1}{\vec{Z}} = \frac{1}{\vec{R}} - \frac{1}{\vec{X}}
\]

An important issue to do is design a high-voltage sinusoidal signal source. The simple design is to use a transistor with output from collector as follows (Figure 6):

Figure 6. AC voltage circuit.

The alternating current from the source flows through the sample, produces voltage difference measured by a dual oscilloscope. The complex impedance is determined by reading maximum Voltage and maximum current:

\[
\vec{Z} = \frac{V_0}{I_0} \text{ or } \vec{Z} = \frac{V_{rms}}{I_{rms}}
\]
The phase constant between the voltage and current is determined by reading the time difference between the two sinusoidal waves using dual oscilloscope.

![Experimental circuit](image1)

**Figure 7.** Experimental circuit.

The explanation of Figure 7 is as follows, 1 is current source, 2 is signal generator, 3 is DC to AC converter, 4 is rock sample and 5 is oscilloscope.

![Oscilloscope](image2)

**Figure 8.** Method of determining phase constant by observing $\Delta t$ (time difference) and period $T$.

Method of determining phase constant (Figure 8) by observing $\Delta t$ (time difference) and period $T$ of the sinusoidal wave of the input sinusoidal wave before passing through the sample and sinusoidal wave after passing through the sample by employing dual input oscilloscope. The phase constant is determined as $F = \frac{\Delta t}{T} \times 2\pi$ radian.

3. Results and Discussion
The measured rock samples from Halmahera island are shown in the following table:
### Table 1. Physical view of the rock samples.

| No. | Samples code | Pictures | Remarks          | No. | Samples code | Pictures | Remarks          |
|-----|--------------|----------|------------------|-----|--------------|----------|------------------|
| 1   | KKE 02       | ![Picture](image) | cylinder         | 8   | LER MH 02A   | ![Picture](image) | cylinder         |
| 2   | LER MH 01    | ![Picture](image) | cylinder         | 9   | KKW 02       | ![Picture](image) | Half cylinder    |
| 3   | LER MH 02    | ![Picture](image) | cylinder         | 10  | LER 02-ST    | ![Picture](image) | Half cylinder    |
| 4   | KKE 02       | ![Picture](image) | Not perfect      | 11  | KKW 01       | ![Picture](image) | Half cylinder    |
| 5   | LER MH 06    | ![Picture](image) | cylinder         | 12  | KKE 01       | ![Picture](image) | Half cylinder    |
| 6   | LER MH 01    | ![Picture](image) | cylinder         | 13  | LER 01-ST    | ![Picture](image) | Half cylinder    |
| 7   | LER MH 06A   | ![Picture](image) | cylinder         | 14  | KKE 01       | ![Picture](image) | Half cylinder    |

Table 1 presents the number of the rock samples along with the physical view, and table 2 presents the results of measurements as described in Figures 7 and 8.

### Table 2. Results of electrical measurements when input by a sinusoidal wave.

| No | Sample code | Frequency (Hz) | Current rms (μA) | Voltage rms (mV) | No | Sample code | Frequency (Hz) | Current rms (μA) | Voltage rms (mV) |
|----|--------------|---------------|------------------|------------------|----|--------------|---------------|------------------|------------------|
| 1  | KKE 02       | 10            | 1.7              | 60               | 8  | LER MH 02A   | 10            | 40200            | 1800             |
|    |              | 100           | 13.2             | 30               |     |              | 100           | 4580             | 360              |
|    |              | 1000          | 165             | 1600            |     |              | 1000          | 10.6             | 116              |
| 2  | LER MH 01    | 10            | 109.5            | 3600            | 9  | KKW 02       | 10            | 124.7            | 200              |
|    |              | 100           | 16.9             | 1200            |     |              | 100           | 1238             | 170              |
|    |              | 1000          | 29              | 130             |     |              | 1000          | 1.8              | 1.2              |
| 3  | LER MH 02    | 10            | 9390            | 6000            | 10  | LER 02-ST    | 10            | 80              | 1200             |
|    |              | 100           | 160             | 1500            |     |              | 100           | 100.3             | 110              |
Tables 3, 4, and 5 present the calculation results to determine $\sigma$ (conductivity) and $F$ (phase constant).

### Table 3. The electrical conductivity results of the halmahera’ rock samples.

| No | Sample code | Depth (m) | $\sigma$ (mho) | $\bar{\sigma}$ (mho) | $\sigma$ (mho) | $\bar{\sigma}$ (mho) |
|----|-------------|-----------|---------------|-----------------------|---------------|-----------------------|
| 1  | KKE 02      | 2.9 - 3.05| 28.333        | 190.486               | 440.000       | 103.125               |
| 2  | LER MH 01   | 10 - 10.2 | 30.417        | 89.192                | 14.083       | 223.077               |
| 3  | LER MH 02   | 18.7 - 18.85| 1565.000     | 1012.778              | 106.667      | 1366.667              |
| 4  | KKE 02      | 23.4 - 23.55| 1190.000     | 3073.860              | 7331.579     | 700.000               |
| 5  | LER MH 06   | 25.8 - 25.95| 10909.091    | 8112.951              | 13404.762    | 25.000                |
| 6  | LER MH 01   | 26.65 - 26.8 | 386.364      | 2838.724              | 5692.308     | 2437.500              |
| 7  | LER MH 06A  | 39.05 - 39.2 | 108307.692   | 62602.564             | 79266.667    | 233.333              |

Whereas the $F$ constant is presented as follows:
### Table 4. The F phase constant of the rock samples.

| No | Sample code | Frequency (Hz) | φ (μs) | φ (rad) | No | Sample code | Frequency (Hz) | φ (μs) | φ (rad) |
|----|-------------|----------------|--------|---------|----|-------------|----------------|--------|---------|
| 1  | KKE 02      | 10             | 0      | 0       | 8  | LER MH 02A  | 10              | 0      | 0       |
|    |             | 100            | 2      | 0.0002  |    |             | 100             | 0      | 0       |
|    |             | 1000           | 20     | 0.02    |    |             | 1000            | 0      | 0       |
| 2  | LER MH 01   | 10             | 0      | 0       | 9  | KKW 02      | 10              | 10     | 0.0001  |
|    |             | 100            | 1      | 0.0001  |    |             | 100             | 2      | 0.0002  |
|    |             | 1000           | 0      | 0       |    |             | 1000            | 0      | 0       |
| 3  | LER MH 02   | 10             | 0      | 0       | 10 | LER 02-ST   | 10              | 0      | 0       |
|    |             | 100            | 1      | 0.0001  |    |             | 100             | 2      | 0.0002  |
|    |             | 1000           | 20     | 0.02    |    |             | 1000            | 0      | 0       |
| 4  | KKE 02      | 10             | 0      | 0       | 11 | KKW 01      | 10              | 0      | 0       |
|    |             | 100            | 0.5    | 0.0005  |    |             | 100             | 2      | 0.0002  |
|    |             | 1000           | 0      | 0       |    |             | 1000            | 0      | 0       |
| 5  | LER MH 06   | 10             | 0      | 0       | 12 | KKE 01      | 10              | 30     | 0.0003  |
|    |             | 100            | 0      | 0       |    |             | 100             | 1.5    | 0.00015 |
|    |             | 1000           | 0.1    | 0.0001  |    |             | 1000            | 0      | 0       |
| 6  | LER MH 01   | 10             | 0      | 0       | 13 | LER 01-ST   | 10              | 10     | 0.0001  |
|    |             | 100            | 0      | 0       |    |             | 100             | 0      | 0       |
|    |             | 1000           | 0      | 0       |    |             | 1000            | 0      | 0       |
| 7  | LER MH 06A  | 10             | -0.5   | -5E-06  | 14 | KKE 01      | 10              | 10     | 0.0001  |
|    |             | 100            | 0      | 0       |    |             | 100             | 2      | 0.0002  |
|    |             | 1000           | -1     | -0.001  |    |             | 1000            | 0      | 0       |

### Table 5. The conductivities along with the F phase constant of the rock samples.

| No | Sample code | Depth (m) | σ (mho) | δσ(mho) | φ (rad) | No | Sample code | Depth (m) | σ (mho) | δσ(mho) | φ (rad) |
|----|-------------|-----------|---------|---------|---------|----|-------------|-----------|---------|---------|---------|
| 1  | KKE 02      | 2.9 - 3.05 | 28.333  | 440     | 0       | 8  | LER MH 02A  | 40.6 - 40.8 | 22333.33 | 12722.22 | 11715.65 |
|    |             |           | 190.486 |         | 0.0002  |    |             |           | 9317.90  | 1500    | 0       |
|    |             |           | 103.125 |         | 0.02    |    |             |           | 1500    | 0       | 0       |
| 2  | LER MH 01   | 10 - 10.2 | 30.417  | 14.083  | 0       | 9  | KKW 02      | 52.1 - 52.2 | 623.5    | 1988.235 | 1370.578 |
|    |             |           | 89.192  |         | 0.0001  |    |             |           | 66.667  | 911.818 | 626.162 |
|    |             |           | 223.077 |         | 0       |    |             |           | 900     | 0       | 0       |
| 3  | LER MH 02   | 18.7 - 18.85 | 1565   | 106.667 | 0       | 10 | LER 02-ST   | 61.1 - 61.25 | 66.667  | 911.818 | 626.162 |
|    |             |           | 1012.77 |         | 0.0001  |    |             |           | 900     | 0       | 0       |
|    |             |           | 1366.67 |         | 0.02    |    |             |           | 900     | 0       | 0       |
| 4  | KKE 02      | 23.4 - 23.55 | 1190   | 7331.579 | 0       | 11 | KKW 01      | 74.5 - 74.65 | 610     | 27142.86 | 9350.952 |
|    |             |           | 3073.86 |         | 0.0005  |    |             |           | 300     | 0       | 0       |
|    |             |           | 700     |         | 0       |    |             |           | 100     | 0       | 0       |
| 5  | LER MH 06   | 25.8 - 25.95 | 10990.99 | 13404.76 | 0       | 12 | KKE 01      | 175.65 - 175.80 | 16.136  | 535.714 | 217.284 |
|    |             |           | 8112.951 |         | 0       |    |             |           | 100     | 0       | 0       |
|    |             |           | 25      |         | 0.0001  |    |             |           | 100     | 0       | 0       |
| 6  | LER MH 01   | 26.65 - 26.8 | 386.364 | 5692.308 | 0       | 13 | LER 01-ST   | 209.10 - 209.25 | 366.981 | 422.222 | 291.273 |
|    |             |           | 2838.724 |         | 0       |    |             |           | 84.615  | 0       | 0       |
|    |             |           | 2437.5  |         | 0       |    |             |           | 84.615  | 0       | 0       |
| 7  | LER MH 06A  | 39.05 - 39.2 | 108307.7 | 79266.67 | -5.00E-06 | 14 | KKE 01      | 213.55 - 213.7 | 98.667  | 857.143 | 328.603 |
|    |             |           | 62602.56 |         | 0       |    |             |           | 30      | 0       | 0       |
If we look up the references regarding the Halmahera island, we found the geological map of the island (Figure 9), and Table 6 presents the Weda Bay (one of the bay in Halmahera island) profile.

![Figure 9. The geological map of Halmahera island (after Farrokhpay, S. et al., 2019)](image)

**Table 6.** The Weda Bay profile (adopted from Cock and Lynch, 1999)

| Horizon          | Mineralogy                      | Ni% | Thickness (m) |
|------------------|---------------------------------|-----|---------------|
| Limestone        | Goethite, Hematite              | 0.8 | 2             |
| Ferruginous saprolite | Ni-rich goethite, Mn oxides | 1.2–1.6 | 4-8           |
| Transition zone  | Mg silicates, Ni-rich saprolite | 1.5–2.5 | 3-4           |
| Saprolite        | Ni-rich saprolite, Talc, serpentine | 0.5–0.8 |             |
| Lower saprolite  | Serpentine, Olivine, pyroxene   | 0.3 |               |

Referring to Tables 5 and 6, we infer that the rock sample number KKE 02 with the conductivity of 190.486 mhos may be the Ferruginous saprolite goethite with a Ni percentage of 1.2 – 1.6. The rock sample, whose number is LER MH 01, maybe from the transition zone because the conductivity of the sample is 89.192 mhos (lower than the conductivity of KKE 02). The LER MH 02 rock sample with the conductivity of 1012.778 mhos from the depth of 18.7-18.85 m may be from the saprolite with a Ni percentage of 1.5 – 2.5. It has the phase constant $F$ of 0.1 mrad for 100 Hz and 20 mrad for 1 kHz. As mentioned earlier, the phase constant indicates the inductive property of the rock samples, which proportionate to the disseminated metal grain. With increasing depth, the rock samples can be classified as bedrock with large conductivities (Serpentine, Olivine, and pyroxene) and some the phase constant $F$ associated with a Ni percentage of 0.3.
4. Conclusion
This paper has presented the measurement of complex resistivity of rock samples of Halmahera Island. The value of conductivity and the phase constant (from table 5) can deduce the metallic content of the rock samples. The positive value of the $f$ phase constant indicates that the rock samples are inductive, whereas the negative value of the $f$ phase constant indicates the rock samples are capacitive. Sample numbers LER MH 02, KKE 02, LER MH 06, and KKW 02 show this inductive property. Sample number KKW 01 shows a slight inductive property. The metallic grains disseminated in the rock samples are the cause of inductive properties. The greater the conductivity and the phase constant, the greater the metallic disseminated minerals are. The electrode polarization causes this inductive phenomenon.

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References
[1] Cock, G.C., Lynch, J.E., 1999, Discovery and Evaluation of the Weda Bay Nickel/Cobalt Deposits Central Halmahera, Indonesia, PACRIM 99 Congress, AusIMM.
[2] Farrokhpay, S., Cathelineau, M., Blancher, S.B., Laugier, O., Fillippov, L., Characterization of WedaBay nickel laterite ore from Indonesia, Journal of Geochemical Exploration, 2019.
[3] Fu, Haiyan, Interpretation of Complex Resistivity of Rock Using GEMTIP Analysis, A thesis submitted to the faculty of The University of Utah in partial fulfilment of the requirements for the degree of Master of Science, University of Utah, 2013.
[4] Halliday, Resnick, Fundamental of Physics, Wiley, 2007.
[5] Sumner, J.S., Principles of Induced Polarization for Geophysical Exploration, Elsevier, 1976.