



Application of the Time Domain Induced Polarization (TDIP) Method for Detecting Manganese Minerals

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Abstract

Manganese (Mn) is a critical mineral commodity widely used in metallurgy, stainless steel production, and energy-storage technologies. Delineating manganese mineralization in complex carbonate-hosted geological settings requires high-resolution and non-invasive geophysical methods. This study applies the Time Domain Induced Polarization (TDIP) method to delineate subsurface manganese mineralization in North Central Timor Regency, East Nusa Tenggara, Indonesia. Seven survey lines, each 300 m long with a 5 m electrode spacing, were acquired using a dipole-dipole configuration. The resistivity and chargeability data were inverted using a smoothness-constrained least-squares algorithm implemented in Res2Dinv, while three-dimensional spatial modeling was performed using RockWorks15. The inversion results identify three principal subsurface units based on their resistivity and chargeability responses. The first unit exhibits low chargeability (27.3–354 ms) and low-to-moderate resistivity (2.36–10.1 $\Omega\cdot\text{m}$), interpreted as topsoil and overburden of the Maubisse Formation. The second unit is characterized by low-to-moderate chargeability (27.3–463 ms) and very low resistivity (0.27–4.89 $\Omega\cdot\text{m}$), corresponding to scaly clay of the Bobonaro Formation. The third unit exhibits high chargeability (354–790 ms) and moderate-to-high resistivity (10.1–43.2 $\Omega\cdot\text{m}$), interpreted as nodular manganese mineralization hosted within limestone of the Maubisse Formation. The mineralized zones occur predominantly at shallow depths of 5–10 m, with lateral extents of approximately 50–260 m. The integration of 2D inversion and 3D modeling effectively delineates the geometry and spatial distribution of shallow manganese mineralization, providing a subsurface framework for subsequent exploration activities, particularly trenching and drilling.

Keywords: *Time Domain Induced Polarization (TDIP), manganese mineralization, chargeability, Res2Dinv*

INTRODUCTION

Manganese (Mn) is one of the many mineral resources found in Indonesia. Manganese is an important element needed by humans and can be utilized in various ways. In metallurgy, for example, manganese is used in the manufacture of steel; it is also considered a main ingredient in the production of stainless steel and various other aluminum materials. Meanwhile, in the non-metallurgical field, manganese is often used as a basic ingredient in battery production and as an admixture in the manufacture of ceramics and glass. There are many ways to look for the potential presence of manganese beneath the earth's surface; one of them is the use of geophysical methods. An appropriate geophysical method for finding manganese is the geoelectric method.

The principle of the IP method is to observe the polarization effect that occurs due to the induced current passing through it. The measured polarization effect is expressed in terms of chargeability, PFE (Percent Frequency Effect), or MF (Metal Factor), depending on the domain used in the measurement process. The IP method has fairly good accuracy; this can be seen from its ability to detect small amounts of metal minerals, around 0.5% of the rock volume, as anomalies. In the time domain, IP measurement is carried out by passing an electric current into the ground. When the current is stopped, the potential between the two measuring

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Manganese Mineralogy and Ore Genesis

According to Harjanto and Danisworo (2013), manganese is one of the 12 most abundant elements in the earth's crust. There are about 300 types of manganese minerals, but only 13 of them are commonly found in commercial ore deposits. Pyrolusite and psilomelane are the common minerals that form the main manganese ore deposits. Pyrolusite is an iron-gray mineral with a metallic luster, a hardness of 2–2.5, and a specific gravity of 4.8. Pyrolusite, which forms as pseudomorphs after manganite or other manganese minerals, is usually massive or reniform and sometimes fibrous and radial in structure. Pyrolusite typically exhibits a steel-gray to black metallic luster with a hardness of 2.0–2.5 and a specific gravity of ~4.8. Psilomelane is a submetallic, hard hydrated oxide (hardness 5.0–6.0) that frequently forms botryoidal, reniform, or nodular masses associated with secondary weathering and supergene enrichment. Manganese mineralization in North Central Timor is primarily associated with supergene enrichment and residual accumulation within weathered karst cavities and structural fractures of the Maubisse carbonate host rocks. Chemical weathering releases manganese ions from primary silicate or carbonate phases, which subsequently precipitate as manganese oxides and metallic sulfides in shallow nodular forms.

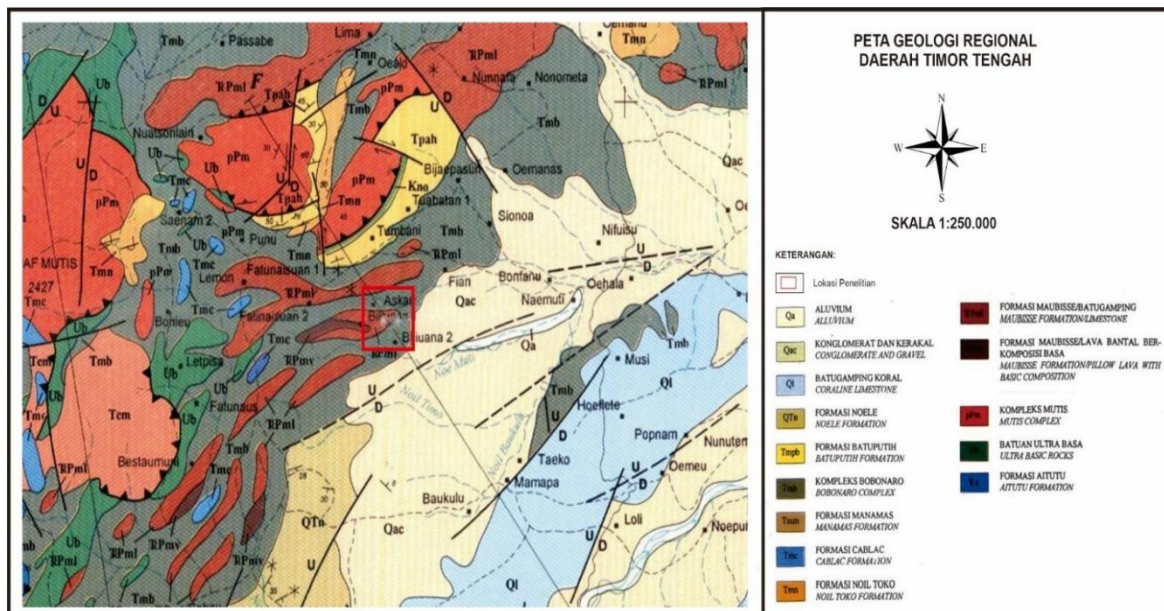


Figure 2. Regional geological map, with the research location on the red line (Tjokrosapoetro & Suwitodirdjo, 1996)

Principles of Time Domain Induced Polarization (TDIP)

The Induced Polarization (IP) method is one of the geophysical methods that utilize the polarization properties caused by an electric current passed through the medium. This method arose because of the limitations of the geoelectric method. One of the measurement techniques of this method is in the time domain; therefore, it is called Time Domain Induced Polarization (TDIP). The IP method is widely used for base metal exploration. One of the measurable parameters, chargeability, can be used to distinguish the subsurface polarizability. High chargeability is an indication of the presence of metallic minerals. These metallic minerals are the target of exploration using the IP method (Yatini et al., 2014). The IP method is used primarily for metal exploration and, on a smaller scale, for groundwater search (Telford et al., 1990). Applying the IP method in a localized area produces more detailed values related to the position of manganese mineralization. This is because the IP method measures both the

resistivity and chargeability parameters.

METHODOLOGY

The data used in this study consist of seven lines oriented northeast–southwest (Figure 1). Each line is 300 meters long, and the electrode spacing is 5 meters. IP data processing is carried out using Res2Dinv software.

Data Processing

IP data processing with Res2Dinv software is done by least-squares inversion. The inversion process aims to estimate model parameters whose response (calculated data) matches the field data. Because the error obtained from the linear inversion equation is still high, the least-squares error criterion is applied to obtain more suitable model parameters. The result of the inversion process is a model of the actual subsurface section.

Data Interpretation

Data interpretation is carried out as part of the research methodology. IP data are interpreted qualitatively and quantitatively, and also by studying the geological data of the research area. Quantitative interpretation of the IP data processing results involves creating 2D and 3D models. The 2D model is made in two forms: the first is a 2D model of each line, while the second is formed by correlating the resistivity and chargeability cross-sections. A 3D model was created using chargeability values with the aim of estimating the distribution of manganese in the study area.

RESULTS AND DISCUSSION

In general, the induced polarization response reflects the ability of the subsurface to store electric charge after a low-frequency electric current or direct current (DC) is injected through two current electrodes and the potential difference is measured at the potential electrodes (Yatini et al., 2019). It is necessary to equalize the resistivity and chargeability scale values to facilitate the interpretation process. The maximum and minimum limits of the resistivity and chargeability values are determined from the dominant values in the inversion results. Based on the inversion results of the field data, the majority of resistivity values range from 0.27 $\Omega\cdot\text{m}$ to 43.2 $\Omega\cdot\text{m}$, so the maximum limit taken for the resistivity cross-section is 43.2 $\Omega\cdot\text{m}$. The chargeability inversion shows that the majority of values range from 27.3 ms to 790 ms, so the maximum limit taken for the IP cross-section is 790 ms.

Chargeability and resistivity values are grouped into three categories: low, medium, and high. The purpose of grouping is to facilitate the interpretation process in the research area. Table 1 shows the grouping of these values.

Table 1. The results of the classification of resistivity and chargeability values

Resistivity ($\Omega\cdot\text{m}$)	Chargeability (ms)	Category
< 2.36	< 354	Low
2.36–10.1	354–572	Medium
> 10.1	> 572	High

A review of the research area literature shows that the resistivity and chargeability values obtained at the research site tend to be higher. This is because an alteration process in the research area converts primary minerals into clay minerals. In addition, some factors that cause variations in resistivity values in the field are the type of rock, the metal mineral content of the rocks, and the

water content of the rocks. Meanwhile, factors that cause variations in chargeability values in the field include the presence of clay minerals in rocks, differences in pore size, and differences in current injection time into the subsurface. Table 2 presents the interpretation of the resistivity and chargeability values.

Table 2. Interpretation of resistivity and chargeability values in the research area

Resistivity ($\Omega\cdot\text{m}$)	Chargeability (ms)	Interpretation	Formation
Medium-High	Medium-High	Manganese mineralized zone in limestone	Maubisse Formation
Low-Medium	Low	Soil	Maubisse Formation
Low-Medium	Medium-High	Clay	Bobonaro Formation

Table 2 shows the distribution of interpretations based on variations in the resistivity and chargeability values below the ground surface. Moderate to high chargeability values indicate the presence of manganese, which causes the polarization effect. The manganese mineralization zone, which is the target of this study, is detected through associated metal minerals in the form of sulfide minerals, so the zone of moderate to high chargeability is interpreted as a manganese mineralization zone. The level of chargeability is also influenced by the amount of metal sulfide it contains.

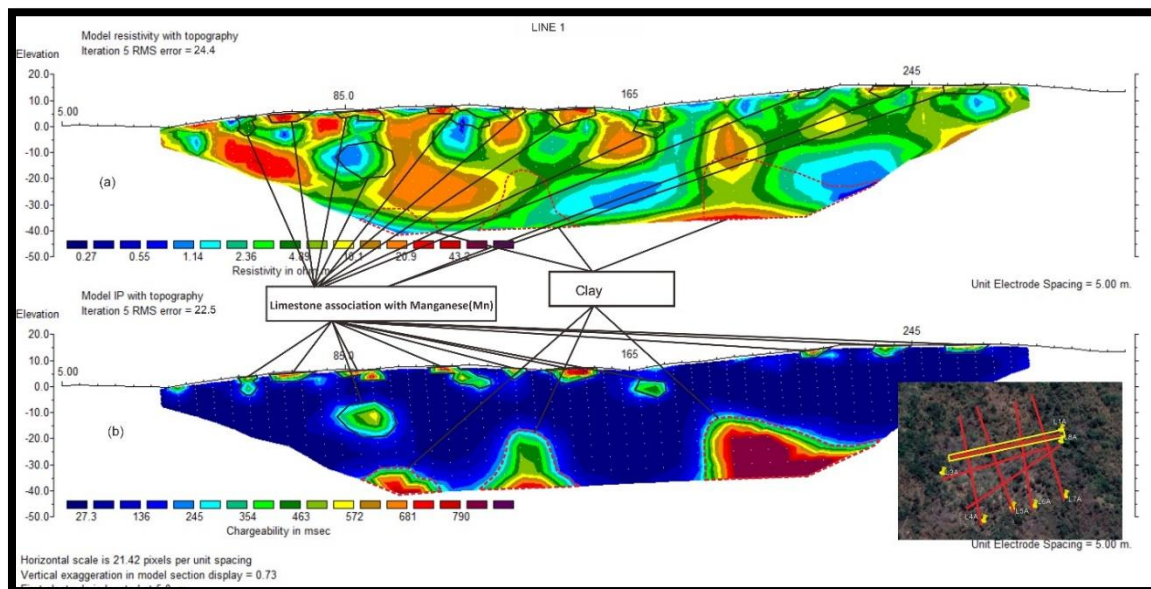


Figure 3. Cross-section of 2D resistivity (a) and IP (b) of Line 1 in the study area, showing nodule-shaped manganese

The cross-section of Line 1 in Field A (Figure 3) shows low to medium chargeability values between 27.3 ms and 463 ms with low to medium resistivity values ranging from 0.27 to 4.89 $\Omega\cdot\text{m}$, which are interpreted as clay from the Bobonaro Formation. Stratigraphically, the Bobonaro Formation consists of scaly clay and boulders of various ages. Low chargeability values of 27.3 ms to 254 ms with low to medium resistivity values ranging from 2.36 to 10.1 $\Omega\cdot\text{m}$ are interpreted as soil belonging to the Maubisse Formation. Stratigraphically, the

Maubisse Formation consists of red-brown to purple limestone interspersed with thin cherts. Moderate to high chargeability values between 354 ms and 790 ms with moderate to high resistivity values ranging from 10.1 to 43.2 $\Omega\cdot\text{m}$ are interpreted as limestone associated with manganese, belonging to the Maubisse Formation.

The mineralized zone is marked by a black outline. Within this outline, the chargeability values fall within the moderate to high range, from 354 ms to 790 ms; referring to Table 2, this indicates a zone of manganese mineral deposition at that location. The zone also has moderate to high resistivity values of 10.1 $\Omega\cdot\text{m}$ to 43.2 $\Omega\cdot\text{m}$, which can be interpreted as limestone associated with manganese minerals. On Line 1 of Field A, the manganese mineralized zones are found as spots along a stretch of 50–260 meters at an estimated depth of 5–10 meters below the ground surface.

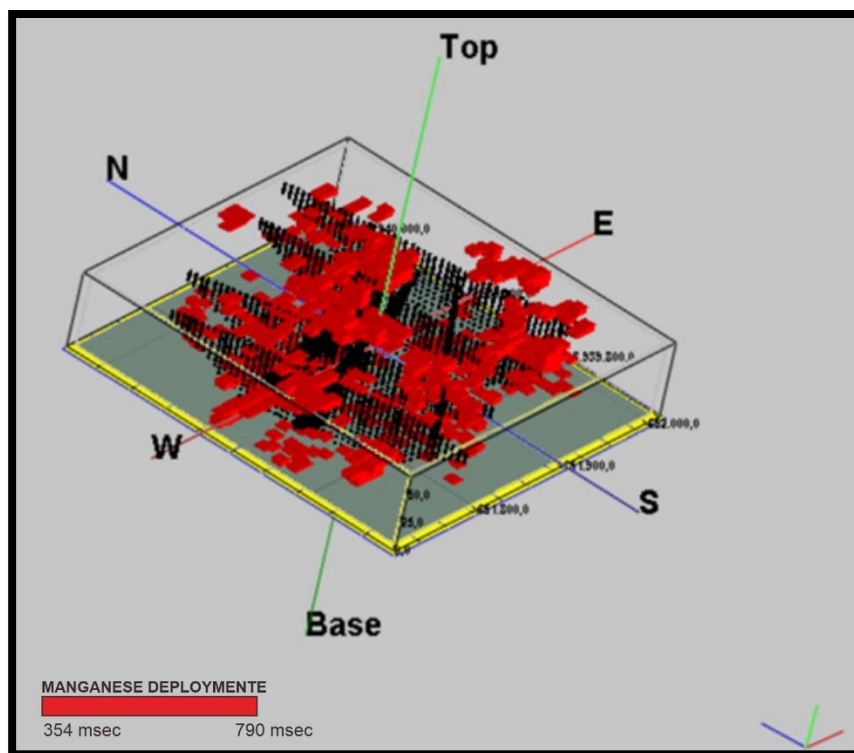


Figure 4. 3D model of manganese distribution in the research area

Manganese distribution

The 3D model in Figure 4 shows the distribution pattern of the research target, namely manganese, with limestone and clay as its host rocks, as indicated by medium to high chargeability values. The nodule-shaped manganese mineralized zone occurs at a depth of 5–10 meters and is associated with limestone with moderate to high chargeability values between 354 ms and 790 ms.

CONCLUSION

In Field A, low chargeability values of 27.3 ms to 254 ms with low to moderate resistivity values ranging from 4.89 to 10.1 $\Omega\cdot\text{m}$ are interpreted as soil. The potential target manganese deposit zones, associated with limestone, have resistivity values of 10.1 $\Omega\cdot\text{m}$ to

more than 43.2 $\Omega\cdot\text{m}$ and chargeability values of 354 ms to 790 ms. The interpretation of the 3D chargeability model shows that manganese is distributed along the survey lines. Manganese in Field A occurs predominantly as nodules and is associated with the surrounding rocks, such as limestone.

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