2D Resistivity and Induced Polarization Measurement for Manganese Ore Exploration

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Abstract. 2D Resistivity and Induced Polarization (IP) survey was conducted to delineate the presence of minerals containing manganese in form of manganese ore. The resistivity method concerns with resistivity \( \text{ohm}\cdot\text{m} \) of rocks which indicates the electrical properties in terms of ability to resist the flow of electrical current. The presence of manganese in rocks generally lowers the resistivity. The Induced Polarization (IP) method deals with chargeability \( \text{in msec} \) which indicates the strength of polarization effects experienced by ions in the vicinity of metallic grains in rock. The presence of manganese in rocks increases the chargeability of the rock when measured using IP method. The low resistivity zones \(< 5 \text{ ohm.m} \) are situated in the western part, central part, and eastern part of the investigated area. These zones may strongly correlate to the presence of manganese ore. However, these low resistivity zones may have been influenced by the presence of clay or weathered soil. In this case, the high chargeability zones will help in confirming the prospective zones caused by manganese ore. The thicknesses of the manganese ore layer vary from about 5 to 20 m based on the cross-sections. Based on the results, we estimated the geometry of the associated manganese prospective zones for resistivity \(< 5 \text{ ohm.m} \) and chargeability \( > 10 \text{ msec} \).

1. Introduction
Manganese ores are defined as minerals that produce manganese (Mn) which is abundant and very important in metal industry because the necessity of any steel to be made with the addition of manganese. Most of manganese ore deposits are of sedimentary origin consisting of Proterozoic manganese formations, black shale-hosted carbonate deposits, and shallow marine oolitic deposits [1]. Naturally, manganese is formed in combination with iron, laterite and other minerals. Pyrolusite (MnO₂), psilomelane ((Ba,H₂O)₂Mn₅O₁₀), manganite (MnO(OH)), and braunite (3Mn₂O₃, MnSiO₃) are economically the most important manganese ores [2].

Several physical properties of manganese ores that can be effectively investigated by appropriate geophysical techniques are density, magnetic susceptibility, electrical resistivity and dielectric constant. Density is ratio of rock mass to its volume, magnetic susceptibility is degree of magnetization of rock in response to an external magnetic field, electrical resistivity is a measure of how strong a rock resists electric current flow, and dielectric constant is a measure of rock ability to store electric field by experiencing polarization. Table 1 shows the physical properties of manganese ore and its host rocks in typical geological setting [3]. The table shows that resistivity of a type of...
manganese ore may vary significantly in order of magnitude depending on the chemical composition and Mn content with higher possibility of low resistivity for pyrolusite and braunite. This paper deals with the application of two geophysical methods, DC resistivity and induced polarization (IP) methods to delineate or localize the presence of rocks or minerals containing manganese in form of manganese ore.

Table 1. Physical properties of manganese ore and host rocks [3].

| Ore / rock    | Chemical composition | Mn content | Density (g/cc) | Magn. Suscep. $10^{-3}$ CGS | Resistivity (ohm.m) | Dielectric constant |
|--------------|----------------------|------------|----------------|-----------------------------|---------------------|--------------------|
| Pyrolusite   | MnO$_2$              | 63%        | 4.70-5.00      | Paramagnetic                | 5x10$^{-3}$-10      | 2101               |
| Psilomelane  | MnOMn$_2$OH$_2$O     | 3.70-4.70  |                |                             | 4.5x10$^3$          | 2977               |
| Braunite     | Mn$_2$O$_3$Mn$_4$O$_2$| 64.3%      | 4.75-4.82      |                             | 0.16-1.2x10$^{-7}$  |                    |
| Rhodochrostie| MnCO$_3$             | 47.8%      | 3.40-3.60      |                             | 100                 | 6.8                |
| Rhodonite    | MnSiO$_3$            | 41.8%      | 3.40-3.6       | Paramagnetic                | 5x10$^{10}$         | 13-30 Water saturated |
| Jacobsite    | MnFe$_2$O$_4$        |            | 4.95           |                             | 200-3000            |                    |

2. 2D DC Resistivity and Induced Polarization Methods

In resistivity method, basically DC current ($I$) is injected through two metallic electrodes at the surface and potential difference as a result of the current flow in the subsurface is measured by two potential electrodes ($\Delta V$) at the surface. It is convenient to expressed the measured data in terms of apparent resistivity (in ohm.m) as

$$\rho_a = K \frac{\Delta V}{I},$$

where $K = \pi n(n+1)(n+2)a$ is geometrical factor of which is controlled by the configuration used. The configuration and geometry of the measurements will controlled the measured responses (potential) at certain points on the surface that contains information of the true resistivity of the earth at certain depths. The measured apparent resistivity distribution is presented in pseudosection (Fig. 1) where $n$ is the relative spacing between the current and potential electrode pairs [4]. Dipole-dipole array was used in the field measurement by considering that even though it has low vertical resolution, it is very sensitive to deeper lateral variations, making it suitable for deeper sounding [5].

![Figure 1](image-url)
The Induced Polarization (IP) method deals with chargeability (in msec) which indicates the strength of polarization effects experienced by ions in the vicinity of metallic grains in rock. The time-domain IP measurement used in this research where decaying voltage after the current is switched off is measured as shown in Fig. 2. The same Dipole-dipole array was used during the IP survey. Chargeability is defined as the area beneath the decay curve over a certain time interval normalized by the steady-state potential difference [4],

\[
M = \frac{A}{\Delta V} = \frac{1}{\Delta V} \int_{t_1}^{t_2} V(t) dt.
\]

Figure 2. Chargeability in time domain IP measurement [4].

3. Area of Measurements
The survey area is about 2000m x 500m in a relatively homogeneous morphology with declining hills from north to south as shown in Fig. 3. Chaotic deposits of scaly clay are obvious in the area accompanied by the presence of red mudstones which serve as the country rocks for Mn mineralization beneath limestone. At same places, fragments of manganese ore in form of nodules and megaliths embedded in turbidite and olistotromes deposits.

There are 70 lines of resistivity and IP measurements, each line is 550 m long trending mostly at N-S direction. Distance between sounding point in each line is 10 m, and distance between the lines is 50 m.

Figure 3. Area of DC Resistivity and Induced Polarization surveys (left); example of manganese ore fragment in the field.

4. Results and Discussion
Both apparent resistivity and chargeability data for all lines were tabulated in pseudosections which were then inverted numerically using RES2DINV program [6] which transformed the pseudosections into models of true resistivity and chargeability as a function of lateral and vertical (2D) distances (Fig. 4). Data processing results in form of resistivity and chargeability sections are shown in Fig. 5.
In almost all sections, resistivity values range between 1 and 100 ohm.m which is considerably low from overall perspective. This feature may be attributed to the presence of manganese ore and/or clay matrix or rocks with low bulk resistivity. The rocks with manganese ore content are interpreted to have resistivity < 5 ohm.m. However, to strengthen the reliability of the results, the resistivity sections are compared with chargeability sections, those who have intersection area between low resistivity and high chargeability (> 10 msec) are considered to be the prospective zones of manganese ore.

Figure 4. Example of sections of observed data and theoretical data whose misfit between them are acceptably minimum to give the best inverted resistivity model (left); examples of the inverted resistivity and chargeability models for a particular line.

The low resistivity zones (< 5 ohm.m) are situated in the western part, central part, and eastern part of the investigated area (Error! Reference source not found.). These zones may strongly correlate to the presence of manganese ore. These low resistivity zones may have been influenced by the presence of clay or weathered soil. In this case, the high chargeability zones will help in confirming the prospective zones caused by manganese ore. The thicknesses of the manganese ore layer vary from about 5 to 20 m based on the cross-sections shown in Fig. 4 and Fig. 5.

Figure 6 depicts the overlay of prospective zones in the investigated area from both resistivity and chargeability in the area. The prospective zones are mainly distributed mainly in the western part, some portion of central part, and eastern part of the investigated area. Areas having intersection of low resistivity and high chargeability are considered the prospective areas with high probability of manganese ore presence.

To constrain the rough estimation of manganese volume, we need to limit the resistivity and IP variation that indicates manganese presence by narrowing the interval of low resistivity (< 5 ohm.m) and the value of chargeability (>10 msec). The prospective zones of manganese ore based on low resistivity and high chargeability have also been reported by Moreira et al. [7]. There are three prospective areas comprising closures at the western part (Area 1), at the center (Area 2), and at the eastern part of the investigated area (Area 3): Area 1 = 83,876 m², Area 2 = 221,598 m², and Area 3 = 58,321 m² and Total Area of the perspective zone = 363,795 m² (36.38 Ha).
Figure 5. Arrangement of 2D resistivity sections in the surveyed area (upper left) and 3D interpolation of low resistivity bodies (lower left) based on the resistivity sections; chargeability sections (upper right) and 3D interpolation of high chargeability bodies based on the chargeability sections (lower right).

Figure 6. Zones of prospective area containing manganese ore
5. Summary
2D Resistivity and IP surveys have been carried in a scaly clay environment where manganese ores are hosted by mudstone. The prospective zones containing manganese ore are characterized by low resistivity (< 5 ohm.m) and high chargeability (> 10 msec) values. The surveyed area is about 100 ha and the prospective zones of manganese ore are about 36.38 Ha. However, this figure has to be validated after incorporation of borehole data from the field which will correct the estimation more accurately.

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References
[1] Krivenko, V. V., Ovcharuk, A. N., Taran, A. Yu., Filev, A. S., Oleynik, T. A., Kharitonov, V. N. (2010) “Investigation of Chemical and Mineralogical Composition of Manganese Ores From Central Asia Deposits”, Metallurgical and Mining Industry, Vol. 2, No. 1, pp 7-11.
[2] Indian Minerals Yearbook 2013 (2015) “Manganese Ore”, Govt. of India, Ministry of Mines, Indian Bureau of Mines.
[3] Murthy, V.S., Madhusudan Rao, B., Dubey, A.K., Srinivasulu (2009) “Geophysical exploration for manganese-some first hand examples from Keonjhar district, Orissa”, J. Ind. Geophys. Union, Vol.13, No.3, pp.149-161.
[4] Kearey, P., Brooks, M., Hill, I. (2002) “An Introduction to Geophysical Exploration”, Blackwell Science Ltd.
[5] Reynolds J. M. (1997) "An Introduction to Applied and Environmental Geophysics", John Wiley & Sons Ltd.
[6] Loke M.H., Barker R.D. (1996) “Rapid leastsquares inversion of apparent resistivity pseudosections by a quasi-Newton method”, Geophysical Prospecting, 44, pp. 131-152
[7] Moreira, C.A., A.A., Borges, M.R., Vieira, G.M.L., Filho, W.M., Montanheiro, M.A.F (2012) “Geological and geophysical data integration for delimitation of mineralized areas in a supergene manganese deposits”, Geofisica internacional, 53-2, pp. 199-210.