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Integrative Geophysical Approach for Enhanced Iron Ore Detection: Optimizing Geoelectrical and Geomagnetic Methods

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ABSTRACT

Geoelectrical and geomagnetic technologies are employed in the Ogololo Sub-District of Sojol District, Donggala Regency, Central Sulawesi, Indonesia, to offer more accurate subsurface information. This is done to rectify inherent deficiencies in the deposit model that impede mineral exploration. The selection of these methods relied on their strong complementarity and effectiveness. Geomagnetic surveys are very effective in identifying the magnetic properties of minerals with high iron levels. On the other hand, geoelectrical surveys are highly effective in distinguishing between ore and host rock by measuring resistivity. Our approach enhances previous methods for iron ore prospecting by using a unique combination of these strategies. To make the interpretation more precise, we employed meticulous modeling and techniques of validation, such as geochemical assays, two-line geoelectrical testing, and five-line geomagnetic observations. Our careful division of iron ore and granitoid bodies, which have resistivity values ranging from 170 to 1146Ωm and 685.7 to 7671.1Ωm, respectively, and geomagnetic anomalies ranging from -650nT to +1700nT, aligns with iron ore content between 61.09 to 97.12%. This clearly shows our significant advancement compared to previous techniques. This combination not only enhances the precision of subsurface condition analysis but also introduces a novel methodology for resource investigation, distinguishing our work in the geophysical exploration sector. Our findings underline the fact that places with substantial magnetic fields are likely electrically conducting structures, which could imply huge iron ore deposits.

1. INTRODUCTION

Indonesia has iron ore deposits in several areas; however, they are rather restricted. Iron ore deposits can be found in several notable areas in Indonesia. These include Central Kalimantan [1, 2], which is known for its magnetite and hematite iron ore, as well as South Kalimantan, Southeast Sulawesi, South Sulawesi, Cilacap Beach, Lampung, South Sumatra, Jambi, Aceh, Pelabuhan Ratu, North Sumatra, West Sumatra [3], and Central Sulawesi [4]. West Sumatra is particularly recognized for its titan iron ore, while Central Sulawesi is home to laterite iron ore. Donggala Regency in Central Sulawesi Province is notable for its iron veins found in the Bou and Balukang districts. These veins, ranging from 2-4 cm, are located inside basalt fissures and contain reserves of iron ore. These places are renowned for their elevated magnetic intensity. Furthermore, in the Bayang area, iron ore minerals are found near the border where granite and andesite intrusion contact.

This emphasizes the geological variety of the region. Contact metasomatism has an impact on the formation of intrusive rocks like andesite, diorite, and dacite [4, 5]. This is evident in the metamorphic contact between the Tinombo creation and intruding rocks, which aids in the production of iron ore in Donggala [6]. The identification of iron ore resources has stimulated mining activities, leading to substantial economic advantages for the local community via the generation of income, employment opportunities, and the promotion of the development of other sectors. These important mineral resources have had a significant impact on Indonesia's economic development.

Geophysical methods are crucial for studying the underground properties of a specific area that may contain valuable mineral deposits, facilitating the identification of mineral resources. Consequently, mistakes in selecting and using geophysical methods might result in monetary damages. Incorrect deposit models will eventually result in inaccurate reserve calculations [7]. The magnetic data does not exhibit any noticeable response. Electromagnetic survey experiments have detected anomalies in several mineralized zones [8, 9]. The geoelectric resistivity investigation done in the Ogololo area revealed that the resistivity values of granite rock and iron ore were equal. Hence, it is essential to modify the survey approach to precisely determine the exact position of iron ore deposits. The precision of geophysical methods used to assess subsurface conditions is vital for the efficacy of natural resource exploration. Improperly choosing or using these approaches may lead to erroneous deposit models and imprecise assessments of mineral reserves. For instance, when an ore body is not detected in magnetic data, it indicates that its magnetic properties closely resemble those of the surrounding materials. This is a significant issue since magnetic surveys are an essential technique for locating mineral deposits. Precise interpretation of electromagnetic surveys is essential for avoiding misconceptions regarding subsurface conditions. A challenge arises during geoelectric resistivity investigations, particularly in the Ogololo area, where distinguishing between granite and iron ore becomes problematic due to their same resistivity results. There is a risk of incorrectly understanding geological data. To address these complexities, it may be essential to implement a complete approach that integrates many geophysical methods, leverages advancements in technology, and combines additional geological data to enhance models and achieve accurate characterization of mineral deposits.

This research aims to improve the efficiency of iron ore exploration in the Ogololo Sub-District, Central Sulawesi, by using a combination of geoelectrical and geomagnetic approaches together with geophysical modelling and validation. This is accomplished by using geomagnetic and geoelectrical resistivity techniques, which use the Earth's magnetic field to identify iron ore deposits under the Earth's crust. By optimizing exploration methods, our goals are to accurately and efficiently identify potential iron ore deposits, minimize exploration costs by reducing the need for extensive drilling, and improve the overall success rate of finding economically viable ore bodies. In addition, through the integration of various methodologies and evaluations, our objective is to acquire a thorough comprehension of the geological formations and mineral makeup of the area, resulting in more knowledgeable decision-making throughout the exploration and mining procedures. In essence, the objective is to optimize the efficiency of exploration endeavors and enhance the probability of uncovering rich mineral resources. The research further integrates petrographic, mineragraphic, and geochemical investigations to discern the many kinds of minerals found in rocks, as well as the primary elements present in the region's ore minerals.

2. GEOLOGY OF STUDY AREA

The study area in regional geology is part of the geologic map of the Tolitoli quadrangle [10]. The topography may be classified into three primary morphological divisions: towering mountains, gently inclined hills, and level lowlands or alluvial plains. Radial and dendritic drainage patterns are often seen in volcanic areas. The Morphology Unit, known for its undulating to rough topography, is situated in the central part of the southern section of the study area. The elevation range of the area extends from 100 to 800 meters above sea level. Bukit Losung, Langgas, and Ogololo are significant geographical points that indicate the range of height. Dendritic drainage patterns and river profiles that display a "U" shape on the slopes and transition to a "V" shape on the hilltops are common. These places often have several completely formed waterfalls and somewhat dense vegetation. On the other hand, the Lowland Morphology Unit, which is also referred to as the Alluvial Plains, is located in the western portion of the study region and covers a range of elevations from sea level to 80 meters. The study area is characterized by rolling topography, with elevations ranging from 170 to 320 meters above sea level, and slopes that may vary from 0 to 300 degrees. The broad river cross-sections in this region are characterized by loose stones that have developed due to the weathering of rock formations [11].

Derived from regional stratigraphy, the research area comprises seven formations categorized by age: Quaternary rocks and Tertiary rocks. Quaternary rocks encompass alluvial and coastal deposits, lake and river deposits, limestone, and Celebes molasses, distributed in the study area's western, southeastern, and eastern parts. Tertiary rocks include marine sedimentary rocks, Tinambo Ahlburg Formation, Tinambo Formation, and Intrusive rocks, distributed in the southern, northern, and northeastern parts (Figure 1).

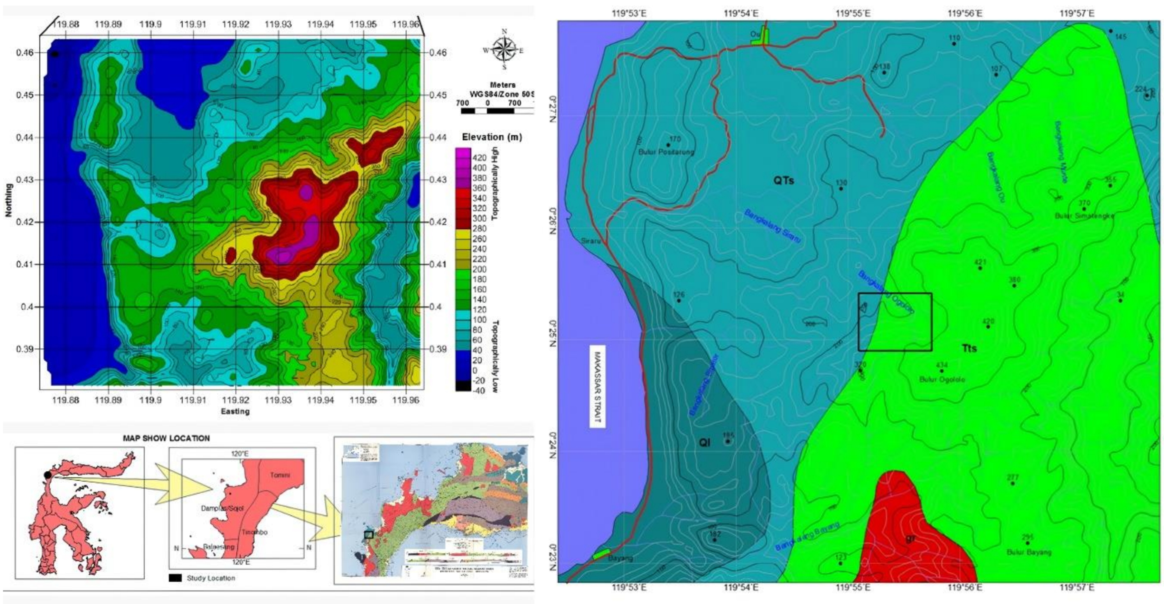

Figure 1. Geological map and altitude map of the research area are part of the geological regional sheet map of Tolitoli, North Sulawesi

The Tinombo Formation consists of various rock types such as phyllite, phyllite slate, quartz sand, siltstone, quartzite, hornfels, red shale, red chert with radiolarian, and volcanic rocks. Schistose quartzite is formed where this rock is intruded by granite, especially in the upper reaches of the Palasa River. Intrusive rocks include andesite, diorite, syenite, and lamprophyre, with granite, syenite, diorite, and adamellite being predominant [12, 13]. Adamellite intrudes through Middle Miocene sedimentary rocks, with ages ranging from Middle Miocene to Upper Miocene based on potassium-argon dating.

Sedimentary rocks that intruded by granite formed schist quartzite and have gradually transformed into greenschist formations, merging with the Tinombo Formation, originating between the Upper Cretaceous and Lower Oligocene epochs. In Donggala, the presence of iron ore deposits is intricately connected to the dynamic processes of tectonic activity and mineralization [1]. Tectonic fault structures play a pivotal role in this geological process that facilitates the intrusion of magmatic predominantly comprising granitoid rocks, into the Tinombo Formation. As magma intrudes and undergoes crystallization within fault zones the accompanying processes of metasomatism and contact metamorphism form iron ore deposits. These geological phenomena result in the enrichment of fluids with various base metals, including the valuable resource of iron ore.

3. METHODOLOGY

The study area is located in the Ogololo Region of Ou Village, Sojol District, Donggala Regency, in Central Sulawesi Province, as seen from an administrative standpoint. The place is positioned between the latitudes of 0°25'07"SL and 0°25'15"SL, and the longitudes of 119°55'23"EL and 119°55'33"EL. The study location is reasonably accessible and can be reached from Palu City in about five hours by motorized vehicles, such as motorcycles and cars (Figure 2).

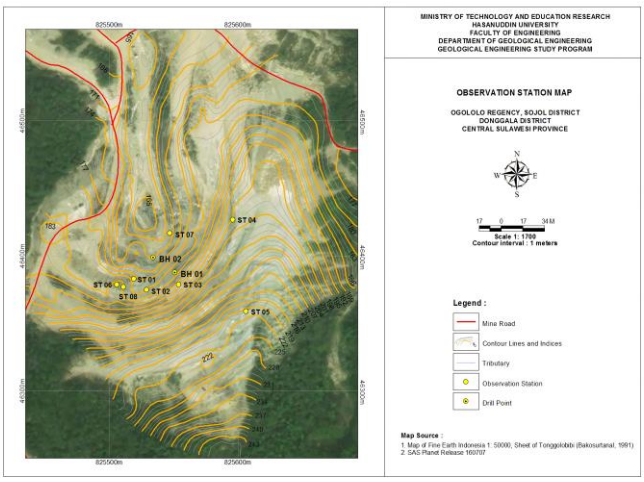

Figure 2. The locations for outcrop analysis, and rock sampling, as well as the trajectories for geoelectrical and geomagnetic measurements

The geoelectric resistivity data was obtained using a Naniura NRD 300 HF resistivity meter equipped with a Wenner-Schlumberger measuring setup. The Wenner-Schlumberger configuration is used for subsurface investigation because of its ability to provide high-resolution pictures of the underground and its exceptional sensitivity in detecting both vertical and horizontal variations. The setup is simple and effective, enabling robust signal reception, hence enhancing the quality of acquired data and facilitating the identification of various subterranean minerals. Researchers may collect exact geoelectric data by using the Naniura NRD 300 HF resistivity meter. This data can then be accurately mapped using GPS to provide a dependable picture of the earth's strata. There were five geoelectric tracks in all, with lengths ranging from 300 to 450 meters. The minimum distance between electrodes was established at 5 meters. To precisely map the measurement tracks, GPS coordinates were captured at regular intervals of 5 meters between the electrodes. This allowed an accurate spatial depiction of the measurement sites on the map.

Additionally, the use of two GSM 19T magnetometer detectors to gather geomagnetic data at each station supplemented the geoelectric data. An individual device located at the central station was used to correct the geomagnetic data gathered at each station. The data collection for geomagnetic observations used a closed-loop methodology, commencing and concluding at the same initial site. This approach allows for the detection of any discrepancies or deviations in the data by comparing the original and final measurements. If any discrepancies arise, they may make the necessary modifications to rectify any inaccuracies. By using this method for the 2138 observation stations, they can ensure the precision and dependability of the geomagnetic data over the whole survey region.

Rock samples were collected from the field, namely from exposed rock formations and iron ore deposits. Furthermore, the sampling procedure included the accurate drilling of vertical cores at two specific places. The sample preparation process in the laboratory was meticulously carried out to ensure that the samples were suitable for analysis.

For thin section preparation, the samples underwent several key steps. Initially, the samples were carefully selected to represent the lithological variations observed in the field. Subsequently, they were cut to size using diamond saws to obtain thin sections with precise dimensions. Following this, the samples were mounted on glass slides using an appropriate adhesive, ensuring that they were securely attached and free from any contaminants. The mounted samples were then ground to a uniform thickness using grinding equipment to achieve optimal transparency for microscopic analysis. Finally, the thin sections were polished to a high degree of smoothness to facilitate clear observation under the polarization microscope.

Following that, a petrographic analysis was carried out to identify the precise rock type as the host for the iron ore, together with the adjacent rock formations present in the study area. Furthermore, a mineragraphic study was undertaken to accurately determine the specific types of ore minerals and their accompanying textures. Sample preparation took place at the preparation laboratory, while the petrographic analysis was conducted in the Laboratory of Mineral Optics in the Department of Geology at Hasanuddin University. The inquiry included the analysis of thin and polished samples using a Nikon Type LV 100ND Polarizing Microscope.

4. RESULT AND DISCUSSION

4.1 Lithology

The lithology of the investigated region mostly consists of intrusive rocks with varying silica concentrations, ranging from acidic to very silicic. The rock types present include diorite, granodiorite, and granite. Diorite is different from other rocks because it has hornblende, biotite, and plagioclase minerals that are fully crystallized. The presence of these minerals imparts a discernible texture characterized by equally distributed grains. The diorite has crystals that often display clear or somewhat clear shapes. Granodiorite is a kind of rock that consists of hornblende, biotite, plagioclase, and quartz. The substance has a crystalline structure that stands out for its evenly spaced grains and precisely formed crystals. The granite found in this region is holocrystalline and has a light grey color. The sample has a rough texture and consists mostly of quartz, orthoclase, and biotite, with minor quantities of plagioclase minerals (Figure 3).

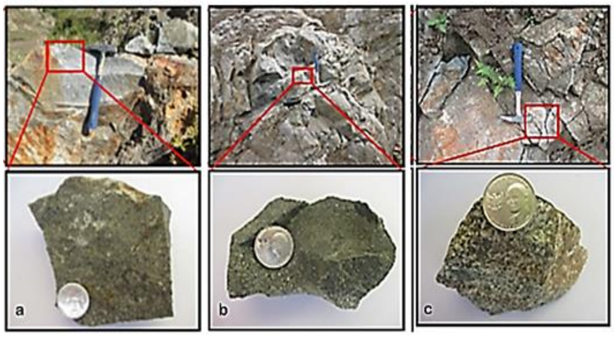

Figure 3. Displays outcrops and rock samples, diorite (a), granodiorite (b), and granite (c)

4.2 Core sample

The BH-01 drill core from the Ogololo Region exhibits diorite with a conspicuous visual aspect. The color of the object varies from dark green to black-gray, and it has a holocrystalline structure. The texture of the rock is coarse-grained, with evenly sized grains, and the majority of the crystals have well-formed to partially formed crystal shapes. The composition of this diorite rock consists of hornblende minerals, biotite, muscovite, and plagioclase. The thickness of the deposit ranges from 1.6 to 19 meters, and it is found at a depth of 20.35 to 28.80 meters, where iron ore deposits are situated (Figure 4a).

Furthermore, inside the BH-02 drill core of the Ogololo area, we come across granodiorite that exhibits comparable traits. It also exhibits a dark green to black-gray hue and has a holocrystalline structure. The connections between the granules are of equal size, and the crystal formations are mostly well-formed or partially formed. This granodiorite rock consists of hornblende minerals, biotite, muscovite, plagioclase, and quartz. The thickness of the layer ranges from 3 to 16 meters, and it is found at depths between 14.15 and 18.35 meters and 58 to 74 meters, where iron ore reserves are located (Figure 4b).

4.3 Simulation of the resistivity geoelectric method

The simulation involves geoelectric measurements on a magnetic iron ore boulder buried beneath the surface. In this simulation, a route length of 4.8 meters was used, which is assumed to accurately represent the usual distance for performing geoelectric tests. Extending the journey length has the potential to provide a more thorough understanding of the properties of the subsurface [14, 15]. The minimum measurement spacing used is 0.1 meters, which represents the distance between measurement points or electrodes. Reducing the distance between data points might result in more precise information, but it would require more labor in the field [16]. The magnetic iron ore boulder is buried at a depth of 1.06 meters. The depth is essential as it dictates the distance below the surface at which the data are being recorded. Precise characterization of subsurface objects is crucial.

Depth (meters)	Unit Lithology	Lithology symbol	Description
0-9,55	Alluvial / Soil		The alluvial constituent material is composed of clay, claystone fragments, sandstone fragments, and andesite rock fragments.
9,55-12,55	Granodiorite		This rock has britle fracture at a depth of 11.35 - 12.55 meters. This unit is composed of feldspar minerals, quartz and associated with biotite and hornblende.
12,55-14,15	Diorite		These rocks are dark green and are composed of feldspar, muscovite and biotite minerals.
14,15-18,35	Granodiorite		These rocks are dark green and are composed of feldspar minerals, quartz and associated with biotite and hornblende.
18,35-20,35	Diorite		This rock is dark green to, has a joint structure, frak cructure, vein ferosulfide found with a fissure of 0.5-1 cm at a depth of 19.50 to 20.20 meters, the composition of this rock consists of feldspar / plagioclase, biotite, muscovite and hornblende .
20,35-28,80	Diorite with iron ore body		This rock is dark green to blackish gray, has no joint structure, frak cructure, found magnetite minerals, hematite, quartz, pyrite 20% sulfide, ilmenite minerals, and feldspar minerals and is associated with other minerals.
28,80-35,0	Diorite		This rock is dark green to, has a joint structure / fructure crak at a depth of 28.2-29 m, found slikenslide at a depth of 27.5-29.6 m, hematite and pyrite minerals
35,0-54,0	Diorite		This rock is dark green to black, the composition of this rock consists of feldspar / plagioclase, boitite, muscovite and hornblende.
54,0-58,0	Diorite		This rock is dark green, there is chloritization and milonitization, the composition of this rock consists of plagioclase, biotite and muscovite.
58,0-74,0	Granodiorite		These rocks are dark green in color, there are vertical stocky structures in normal faults, texture of the degree of holocystaline crystallinity with equigranuar relations. This unit is composed of feldspar, quartz, biotite and hornblende minerals.

Depth (meters)	Unit Lithology	Lithology symbol	Description
0-14	Diorite		This rock is black gray to black and white shine, has a massive structure and texture of hypocrystalline crystallinity, 10-60% afanitic - faneritic granularity, euhedral crystalline form, hornblende mineral composition, biotite, muscovite, feldspar / plagioclase, magnetite and pyrite 10 - 60% .
14,0-16,50	Iron Ore		Iron ore is black, massive structure, octtaedral crystal form, the composition of the mineral magnetite, silica, pyrite and ilmenite, feldspar / plagioclase and associated with other minerals.
16,50-20,25	Diorite with iron ore body		This rock is black gray, has a massive structure and texture of hypocrystalline crystallinity, faneritic ingranularity, subhedral crystalline form, the composition of hornblende minerals, plagioclase, magnetite and pyrite 40% at a depth of 16.50-17m. Iron Ore was found at a depth of 19.40 - 19.50 m Iron Ore was found at a depth of 19.90 - 20.25 m
28,80-35,0	Diorite		This rock is black gray to black and white shine, has a massive structure and texture of hypocrystalline crystallinity, 10-60% afanitic - faneritic granularity, euhedral crystalline form, hornblende mineral composition, biotite, muscovite, feldspar / plagioclase, magnetite and pyrite 10 - 60% . Found material resulting from rock fragments at a depth of 19.90 - 20.25 m.

Figure 4. (a) The lithology column is derived from the rock analysis results obtained from core drill BH 01; (b) The lithology column has been established using the rock analysis results obtained from the BH 02 core drill

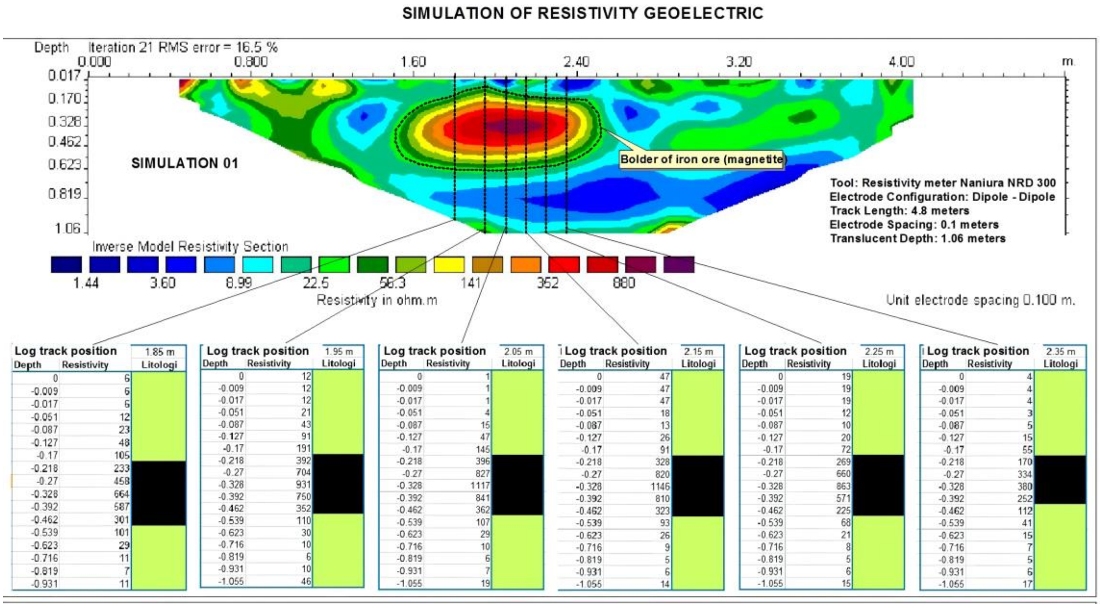

Figure 5. The results of the initial simulation, showcasing a broad spectrum of resistivity values associated with magnetic iron ore, ranging from 170 Ωm to 1146 Ωm

The subject of analysis in this simulation is a magnetic Iron ore boulder, with dimensions of roughly 1 meter in length, 0.5 meters in breadth, and 0.45 meters in height. The size and magnetic properties of this item are both significant factors in determining its impact on geoelectric tests. The boulder is located at a depth that varies between 0.17 and 0.62 meters below the surface. This implies that the boulder is not consistently buried, but rather is found at different depths throughout the trail. This variability may provide useful insights into the vertical variations of geoelectric characteristics. The boulder is located on a track that extends from 1.5 to 2.5 meters. This indicates that measurements are being conducted along a certain trajectory, and the boulder is positioned somewhere within this predetermined span. The simulation's primary result demonstrates a continuum of resistivity values on magnetic iron ore, spanning from 170 Ωm to 1146 Ωm (Figure 5).

The second simulation used a 12-meter track, with a minimum spacing of 0.4 meters between objects and a depth of 2.5 meters. The simulation utilizes a range of rock boulders, such as gabbro, granite, hematite, diorite, and magnetite. The rocks were chosen based on macroscopic descriptions gathered from a research location. The simulation arranges these rock pieces at precise locations along the course. The simulation yields resistivity values for each of these rocks at their corresponding places.

The rocks are arranged along the simulated route in the following order: gabbro at a distance of 3 meters, granite at 3.8 meters, hematite at 5 meters, diorite at 7 meters, and magnetite at 9 meters. The simulatio results demonstrate different resistivity values for each of these rocks. The resistivity range of Gabbro is 2790.1 Ωm to 13098.2 Ωm, granite extends from 685.7 Ωm to 7671.1 Ωm, hematite spans from 745.4 Ωm to 140303.9 Ωm, diorite shows resistivity values between 374.2 Ωm and 5291.8 Ωm, and magnetite showcases a range of 1053.5 Ωm to 5807.2 Ωm (Figure 6). The large range of resistivity values for hematite indicates substantial diversity in its electrical characteristics, which might have major consequences for the geological background or possible resources at the research site.

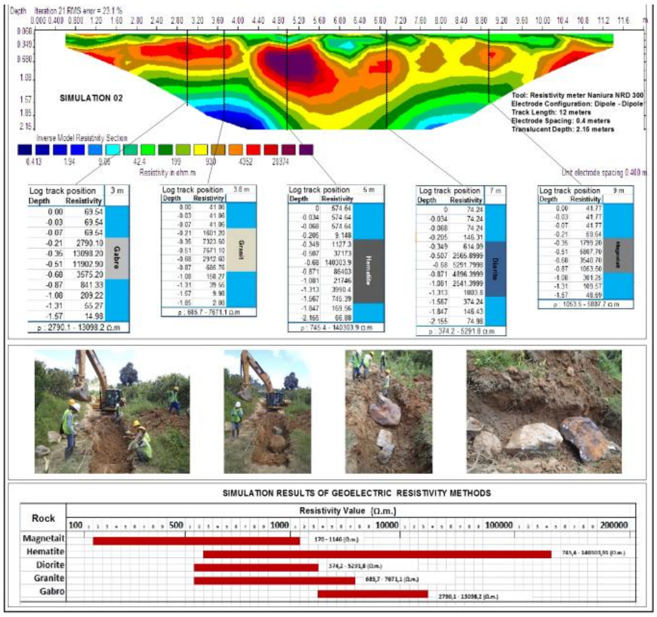

Figure 6. Displays the outcomes of the second simulation, presenting the resistivity values for each rock at their respective positions

4.4 Geomagnetic method simulation

The simulation uses a geomagnetic method to analyze the magnetic properties of a test excavation that includes magnetite and iron ore. The dimensions of the test pit are 2.5 meters in length, 1.2 meters in width, and 2 meters in height. The composition comprises particles of magnetite iron ore. The object, consisting of magnetite iron ore, has a volume of 2 cubic meters and has been confirmed to have a Fe content of 97.12% by geochemical analysis. The simulation included the use of two GSM 19T magnetometers, which were placed at a separation distance of 1 meter. Data collection started at an initial location and concluded at the same destination. The primary aim of the study was to measure the variations in the magnetic field caused by the presence of magnetite iron ore.

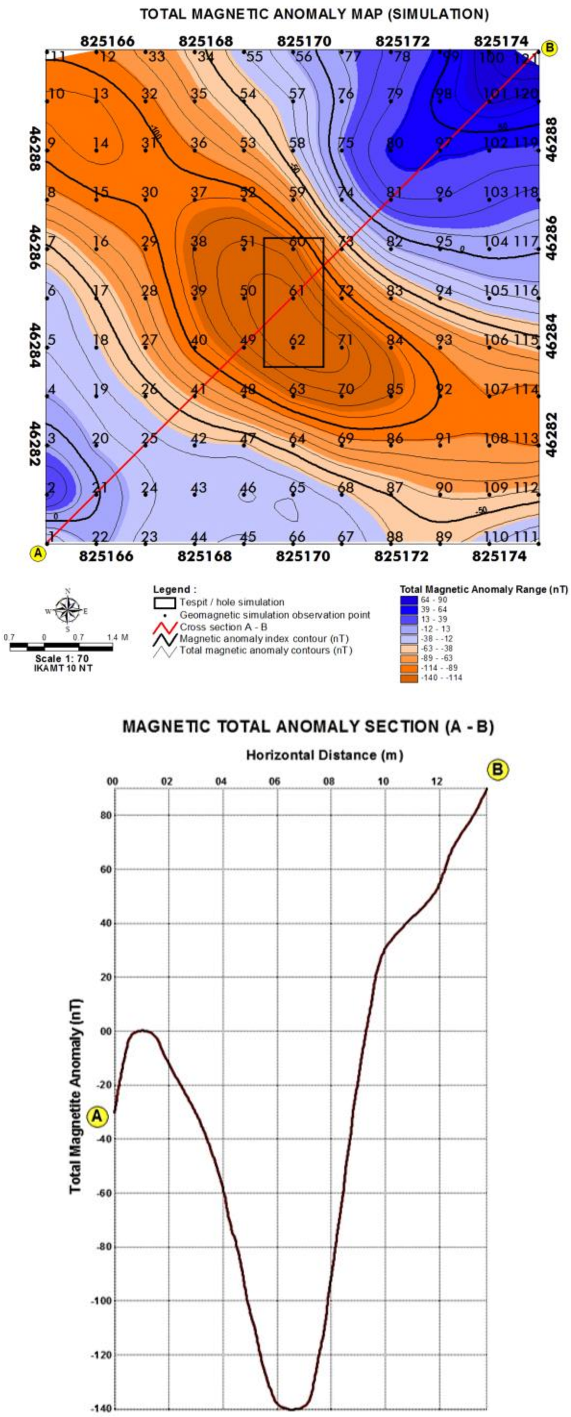

Figure 7. The simulation involves a geomagnetic method at the cross-section, it is evident that the double anomaly pattern is present

The simulation results provide a thorough investigation of the whole magnetic anomaly via cross-sectional analysis. The cross-section shows the existence of a two-fold anomaly pattern. To be more specific, the negative anomalies have a cumulative magnetic anomaly value of -140 nT, whereas the positive anomalies have a cumulative magnetic anomaly value of +90 nT. This technique improves the comprehension and solution of the identified magnetic irregularities. Moreover, a comprehensive analysis of the whole magnetic anomaly cross-section confirms the presence of this dual anomaly pattern. According to the data, negative anomalies have a cumulative magnetic anomaly value of -140 nT, whereas positive anomalies have a value of +90 nT. The cross-sectional investigation improves the comprehension of the magnetic abnormalities identified (Figure 7) by offering more intricate and explicit data.

The simulation verified the existence of magnetite iron ore at a site exhibiting a negative magnetic anomaly of -140 nT, situated at a distance of 6.5 meters. This finding emphasizes the connection between adverse magnetic irregularities and the existence of magnetite iron ore. In addition, the simulation detected a dual anomaly pattern in the magnetic field, characterized by the presence of both negative and positive anomalies. This emphasizes the significant impact of the magnetite iron ore on the local magnetic field.

4.5 Total magnetite anomaly

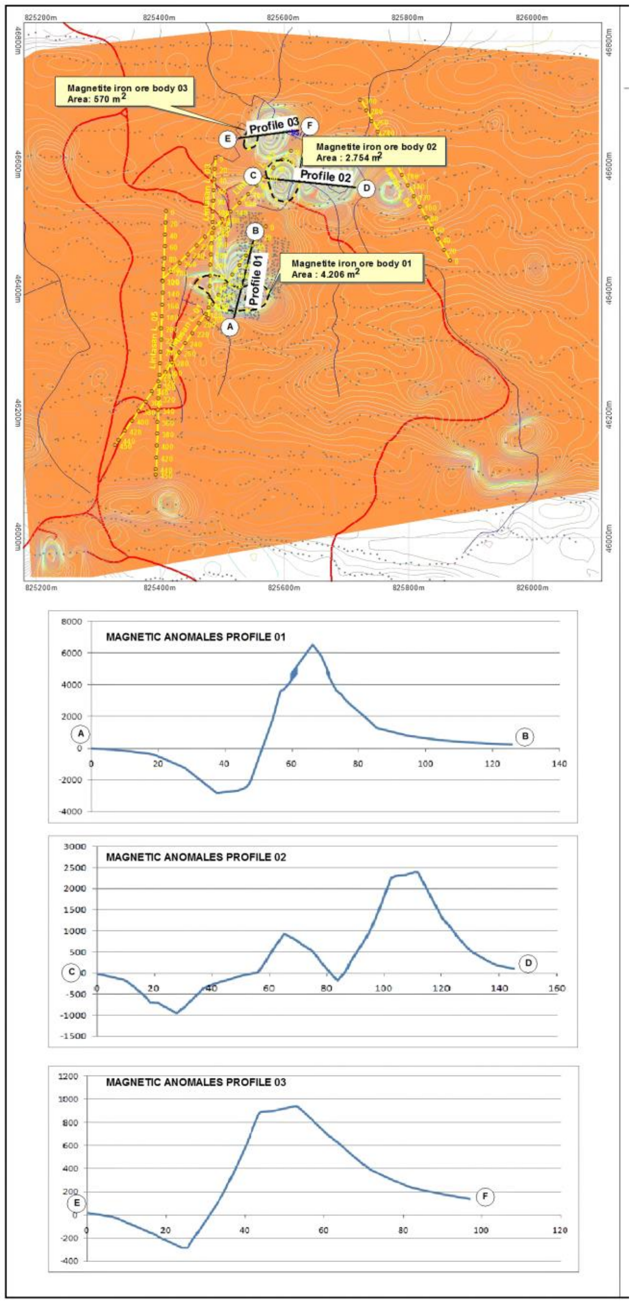

Figure 8. Total magnetic anomaly map of the study area

In the studied region, magnetic anomaly measurements indicate the presence of two different types: positive anomalies ranging from 0 to +6800 nT and negative anomalies from -2800 to 0 nT (Figure 8). An analysis of the magnetic anomaly map has revealed three instances of iron ore bodies exhibiting dual-polar anomalies. The magnetic anomaly profile 01 (AB), which had a length of 127 meters, served as the initial indicator of the magnetic iron ore body 01's presence. The analysis of this profile indicates the presence of positive anomalies ranging from 0 to +6530 nT, while negative anomalies range from -2800 to 0 nT and are particularly concentrated at the 37-meter point on the magnetic anomaly profile 01 (AB). The magnetic iron ore indication 01 is located at the 37-meter location on the magnetic anomaly profile 01 (AB), inside the negative anomaly zone. It covers an area of 4206 m².

The second indication, magnetic iron ore body 02, may be seen inside the magnetic anomaly profile 02 (CD), which extends over a distance of 145 meters. On magnetic anomaly profile 02 (CD), we see positive anomaly values ranging from 0 to +2390 nT, as well as negative anomalies ranging from -900 to 0 nT at a distance of 27 meters. The presence of magnetic iron ore body 02 is detected at the location of a negative anomaly, precisely at a distance of 27 meters on the magnetic anomaly profile 02 (CD). This ore body covers an area of 2754 square meters.

The third indication, known as magnetic iron ore body 03, is identifiable in magnetic anomaly profiles 03 (EF), which have a length of up to 97 meters. The magnetic anomaly profile 03 (EF) has positive anomaly values ranging from 0 to +940 nT, while negative anomalies ranging from -280 to 0 nT are seen at a depth of 23 meters within the same profile. The presence of a magnetic iron ore deposit, known as body 03, has been detected at a location with a negative anomaly. More precisely, it is located at a depth of 23 meters on the magnetic anomaly profile 03 (EF), and it spans an area of 570 square meters. The presence of places with high magnetic strength suggests a significant drop in resistivity, indicating the existence of electrically conductive structures, most likely iron ore deposits [17, 18].

4.6 Optimization of the iron ore exploration method

Table 1. Optimization of the geoelectric resistivity method in the study area

Rock Type	Resistivity Range (Ω.m) [19]	Resistivity Range (Ω.m) (Simulation)
Granite	200 – 100000	685.7 – 7671.1
Diorite	10000 – 100000	374.2 – 5291.8
Granodiorite	100 – 500000	2790.1 – 13098.2
Ore Minerals		
Magnetite	0.01 – 1000	170,0 – 5807,2
Hematite	0.01 – 1000000	745,4 – 140303,9

Table 2. Optimization of the geomagnetic method of the research area

Interpretation	Tonase (ton)	Depth Ore Body (m)	Anomali Magnetik Range (nT)
Simulation	15,78	1	-140 - +90
Magnetite 01	83618	14	-2800 - +6530
Magnetite 02	-	-	-900 - +2390
Magnetite 03	-	-	-280 - +940

Upon analyzing the simulation results obtained from the geomagnetic method and its integration with the resistivity geoelectric method, several notable advantages have emerged. These include a narrower resistivity range for small rocks and ores (Table 1), as well as the observation of distinct paired anomaly patterns for both magnetite and hematite ores (Table 2).

To validate the resistivity values for granite, diorite, and gabbro rocks, was conducted petrographic analysis on five samples of each rock type. The composition of granite rocks comprises a blend of minerals, including quartz (35-50%), orthoclase (30-40%), plagioclase (20-25%), and biotite (5-15%), exhibiting a myrmekitic texture. Diorite, on the other hand, exhibits distinctive features such as subhedral to anhedral mineral plagioclase (35-45%), K-Feldspar (25-35%), quartz (5-7%), and pyroxene (15-20%). Lastly, granodiorite rocks display a mineral composition consisting of potassium feldspar (40-50%), plagioclase (30-40%), and quartz (15-30%), predominantly in the form of euhedral to subhedral crystals (Figure 9).

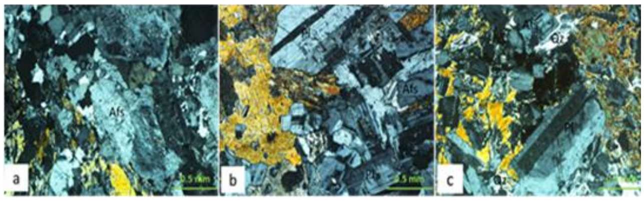

Figure 9. The petrography analysis results of granite (a), diorite (b), and granodiorite (c) validate the resistivity values of the tested rocks using the resistivity geoelectric method

Iron ores, comprising magnetite (Fe_3O_4) and hematite (Fe_2O_3) minerals, are verified through ore petrography and geochemical analysis. Magnetite exhibits isotropic optical properties, high relief, a gray hue, and lacks internal reflection, and pleochroism. In contrast, hematite can be distinguished from magnetite due to its optical anisotropy, ranging from white to gray, and featuring internal reflection in red (Figure 10). The ore mineral samples contain a substantial proportion of the Fe_2O_3 oxide compound, ranging from 50.08% to 96.81%, which is indicative of both magnetite and hematite minerals as confirmed by ore petrography analysis. Furthermore, the presence of a low SiO_2 compound, ranging from 0.94% to 32.09%, underscores the minimal association of iron ore with gangue minerals, a finding supported by the petrography analysis.

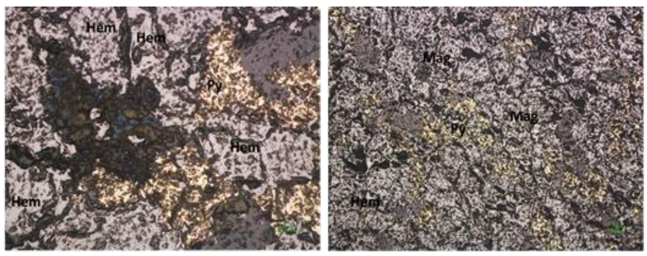

Figure 10. The validation of iron ore body indications through mineragraphy analysis, which identifies the presence of hematite and magnetite minerals

4.7 Discussion

The exploration of iron ore deposits in Indonesia, with its unique geological characteristics, is a topic of both geological and economic importance. Advanced geophysical methods have played a pivotal role in accurately identifying and quantifying these reserves. This discussion will delve into the integration of geomagnetic and geoelectrical methods, their applications, and the significant findings from geophysical simulations. We will also highlight the potential implications for the mining industry and economic development in Indonesia.

The combination of geomagnetic and geoelectrical methods stands out as a noteworthy approach in the exploration of iron ore deposits. These methods leverage the Earth's magnetic field to detect iron ore beneath the surface without invasive procedures, making them efficient and non-destructive. This integration, when combined with petrographic, mineragraphic, and geochemical analyses, provides a holistic understanding of the geological composition and mineral content of the region.

The geophysical simulations carried out have been instrumental in enhancing the precision of mineral exploration [20, 21]. This research has fine-tuned parameters such as path length and spacing to model resistivity values for different rock types, including iron ore. This approach not only helps in accurately detecting iron ore deposits but also distinguishes between various rock types based on their resistivity values. The ability to precisely identify the composition and characteristics of subsurface materials is a significant advantage in mineral exploration.

One of the most remarkable findings from these simulations is the identification of dual-polar anomalies in magnetic data. These anomalies, with their positive and negative magnetic values, serve as key indicators of iron ore bodies. Analyzing these anomalies to pinpoint the location and extent of iron ore deposits, greatly improves the efficiency and reliability of exploration efforts.

The resistivity values obtained are instrumental in characterizing subsurface objects, such as the magnetic iron ore boulders. Resistivity is a measure of how well a material conducts electricity and can provide insights into the nature and composition of buried objects [22]. The wide range of resistivity values for hematite suggests significant variability in its electrical properties [23]. This variability may be indicative of different geological contexts or variations in potential resources at the study site. The detailed analysis of these resistivity values can lead to a more comprehensive understanding of the geological features in the region.

The integrated geophysical methods employed in the exploration of iron ore deposits in Indonesia, particularly in the Ogololo Sub-District of Central Sulawesi, signify a significant advancement in geological studies. The integration of geomagnetic and geoelectrical methods, coupled with geophysical simulations, has improved the accuracy of detecting and quantifying iron ore reserves. The identification of dual-polar anomalies in magnetic data and the analysis of resistivity values have practical applications in the mining industry. These findings have scientifically significant implications for sustainable resource utilization.

5. CONCLUSIONS

Conclusions from the research results and findings that have been presented are as follows:

• The L_01 trajectory appears to be the most likely site for the iron ore body, displaying a resistivity range of 600 - 8938.7Ωm and an estimated cross-sectional area of 922 m², consistent with magnetite iron ore.

• The magnetic anomalies found in the range of -650nT to +1700nT strongly suggest the presence of electrically conductive structures and potentially indicate the existence of iron ore deposits.

• The resistivity values of the surrounding rock formations, composed of weathered granodiorites, massive granodiorites, and massive diorites, exhibit a wide range, ranging from 600 to 8938.7Ωm.

• The study's confirmation of notably high iron ore content in the area, coupled with the effectiveness of integrating geomagnetic and geoelectrical methods, underscores the importance of these findings for future exploration and mining efforts.

• The range of resistivity and the estimated size of the cross-sectional area make the L-01 trajectory stand out as a great place to look further because it has a high likelihood of holding magnetite iron ore. Moreover, the extent of magnetic irregularities aligns with the existence of conductive formations, often linked to concentrations of iron ore.

• Exploratory teams might use these integrated methodologies as a model for future surveys, perhaps using them in similar geological settings to expedite the discovery and evaluation of mineral resources. Adopting this method would improve the effectiveness of resource exploration, leading to higher output in mining operations and a more comprehensive understanding of the geological features of the area.

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