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Characteristics of Laterite Nickel Based on Geochemical Data and Electrical Resistivity Tomography (ERT) of Ultramafic Rocks in the Sorowako Area, East Luwu Regency

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ABSTRACTS

In laterite nickel exploration, PT.Vale Indonesia Tbk, initialy relied solely on drilling methods to define profile boundaries based on mineral content and rock characteristics, but discrepancies of around 2% between reserve estimates and actual mining outcomes led to the adoption of geophysical methods as a complementary approach in 2014. This study aims to determine the characteristics of laterite nickel profiles by correlating resistivity values with geochemical data. Using Datamine and Leapfrog software, a 3D model of laterite nickel profiles was generated, identifying limonite (0–10 m depth, 201–250 Ohm.m resistivity), saprolite (0–10 m depth, 101–200 Ohm.m resistivity), and bedrock (>10 m depth, 101 to >801 Ohm.m resistivity). Variations in resistivity are influenced by factors such as mineral content and morphology. The volume estimated from resistivity correlation and drillhole data is 1,625,300 m^3 for limonite and 1,902,600 m^3 for saprolite, compared to 1,523,100 m^3 and 1,390,100 m^3 based on drillhole-only data, showing discrepancies of 6% and 27%, respectively. This study provides a clearer understanding of geological modeling using drillhole and ERT data to support laterite nickel ore mining and correlation modeling.

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INTRODUCTION

Laterite nickel is a residual soil material found in ultramafic rocks formed through supergene enrichment and chemical weathering processes. According to the United States Geological Survey (USGS), Indonesia is the world's largest nickel producer, with an estimated output of 1.6 million metric tons, contributing 48.48% of global nickel production in 2022. In addition to being the leading producer, Indonesia also holds the world's largest nickel reserves since 2022, totaling 21 million metric tons. One of the major nickel-producing regions is Sorowako, South Sulawesi, where laterite deposits serve as the primary source of nickel, processed and mined using conventional smelting methods by PT. Vale Indonesia (Fitrian et al., 2020).

In laterite nickel exploration, PT. Vale Indonesia initially used drilling methods to determine the boundaries of laterite nickel profiles based on mineral content and rock sample characteristics, with drillhole spacing of 50 and 25 meters. However, discrepancies of around 2% between reserve estimates and actual mining outcomes prompted the introduction of geophysical methods in 2014. These methods were seen as a complementary approach to optimize exploration by delineating profile boundaries in areas not covered by drillholes or between drillholes.

The geophysical method employed is Electrical Resistivity Tomography (ERT). ERT enables modeling and interpretation by following the contour patterns of resistivity values, producing models that more accurately represent subsurface conditions. This study aims to analyze the characteristics of laterite nickel profiles based on ERT and drillhole data.

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LITERATURE REVIEW

According to Kumarawarman (2016), referencing Golightly (1979), the geology of the Sorowako region can be categorized into three sectors: Sedimentary Rock Units from the Cretaceous period, which include deep marine limestones and cherts, bounded in the west by a west-dipping thrust fault; Ultrabasic Rock Units from the early Tertiary period, typically peridotites that have undergone varying degrees of serpentinization, predominantly located in the eastern region; and a significant fault system within the study area, creating topographic reliefs up to 600 meters above sea level and remaining active, subjecting the region to ongoing erosion. This active erosion has facilitated the development of an economically viable lateritization phase.

Golightly (1979) described the eastern Sulawesi region as consisting of three subduction mélange units uplifted during the pre- and post-Miocene periods. The oldest mélange is composed of schists trending southeast and narrow ultrabasic rock exposures with an advanced geomorphic stage. In contrast, the post-Miocene mélange has undergone widespread weathering, enabling the formation of economically significant laterite nickel deposits, such as those found in Pomala.

Structural Features of the Study Area

As shown in Figure 1, the fault system in Sorowako generates topographic reliefs reaching up to 600 meters above sea level and remains actively eroded. The Matano Fault, characterized by a relatively prominent lineament topography, is an active fault responsible for displacing the Matano Limestone approximately 18 km westward in the northern region. Lake Matano, with a depth of up to 600 meters, is hypothesized to be a graben formed as a result of dilational zones along this fault. South of the fault, Lake Towuti is believed to have shifted from Tambalako due to movements along the Matano Fault. This movement blocked northward water flow along the valley, redirecting it westward toward the Larona River, resulting in the formation of Lake Towuti. These lakes, formed due to the "damming effect" of the fault, act as natural barriers, trapping laterite nickel deposits and regulating erosion rates.

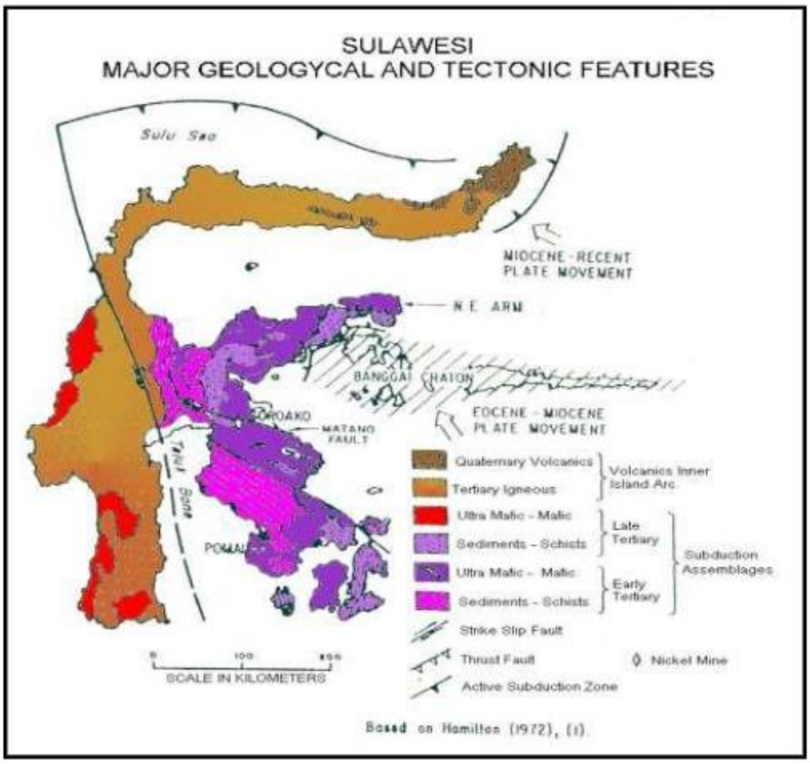

Figure 1 Geological map of the research area

The Type of Nickel Laterite in Sorowako

According to Ahmad (2009), the nickel laterite deposit in the study area is classified as the West Block. This classification is based on several key parameters, such as the degree of serpentinization, ultramafic rock type, rock fraction content, olivine composition, and ore chemistry. This type features

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rugged topography, forming mountainous terrain. The rocks in this area are predominantly harzburgite, containing olivine (approximately 80-90%) and orthopyroxene (approximately 10-20%). Dunite rocks are also found with an olivine content of 90% and minor amounts of chromite minerals. The rocks in this region are typically un-serpentinized or slightly serpentinized, exhibiting a fairly hard material texture. Fresh peridotite boulders are frequently encountered.

Electrical Resistivity Tomography (ERT)

ERT is a geophysical technique used to study the electrical current properties of the Earth and detect them at the surface based on the characteristics of different rock types (Widodo et al., 2013). In this study, resistivity values from ERT reports are correlated with the total elemental content from geochemical reports to develop a profile characterization. Geochemical information provides data on the variation of resistivity values along a surveyed line. The integration of geochemical and ERT data offers an initial depiction of elemental concentrations by observing the ERT cross-section.

This study employs the gradient configuration, a relatively uncommon but high-resolution method, allowing for the acquisition of diverse information by manipulating the geometry of the elements.

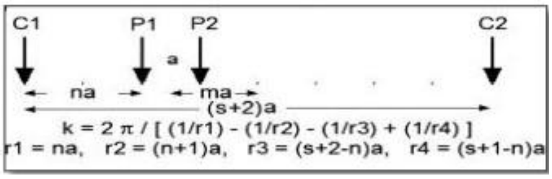

Figure 2 Gradient configuration illustration (Dahlin & Zhuo, 2006)

RESEARCH METHODS

The research location is situated within the concession area of PT. Vale Indonesia Tbk, Nuha District, East Luwu Regency, in the West Block area, South Sulawesi. This study utilized secondary data provided by the company.

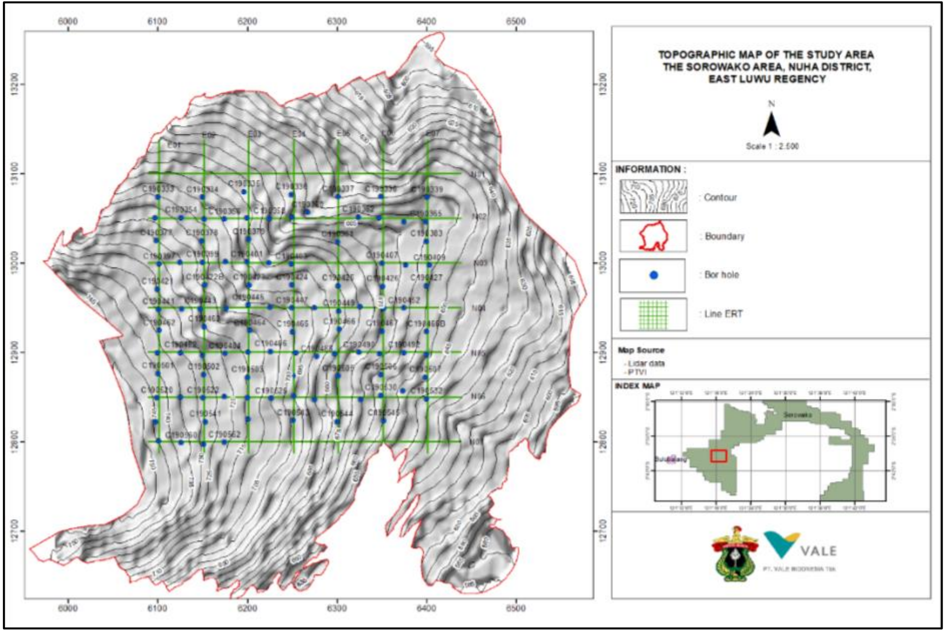

Figure 3 Topographic maps and route maps of the research area

1. Drillhole Data

The data was obtained through field data collection and laboratory analysis, then processed and analyzed to observe the composition of the drill results. This data was used to identify the layers of limonite, saprolite, and bedrock. A total of 102 drillhole points were analyzed, recorded in a spreadsheet format including assay and collar data, and were used to create topographic maps and drillhole point distribution maps.

2. ERT Data

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The ERT (Electrical Resistivity Tomography) data utilized a Gradient Configuration with a total of 14 survey lines: seven oriented east-west and seven oriented north-south. Each line measured approximately 345 meters in length. The processed data consisted of resistivity values and topographic measurements for each line. In general, the interpretation of the data in this study illustrates the stratification system based on the characteristics of the West Block in the study area (PT. Vale Indonesia, 2016) (Figure 3).

The interpretation was carried out by defining and delineating the boundaries of each layer, specifically the bottom boundary of the limonite layer (limonite bottom) and the bottom boundary of the saprolite layer (saprolite bottom) within the nickel laterite profile using Datamine software. The interpretation results from the nickel laterite profile reveal the stratification system of nickel laterite, consisting of limonite, saprolite, and bedrock. The thickness and depth values of each layer's zone were obtained from drillhole data, which served as the basis for identifying the nickel laterite stratification system. The study also assessed the influence of chemical element content, particularly Fe and SiO_2, on resistivity values and the impact of morphology. Subsequently, a geological modeling process was conducted based on two interpretations:

1. Interpretation from drillhole to drillhole.
2. Interpretation of resistivity values correlated with drillhole data.

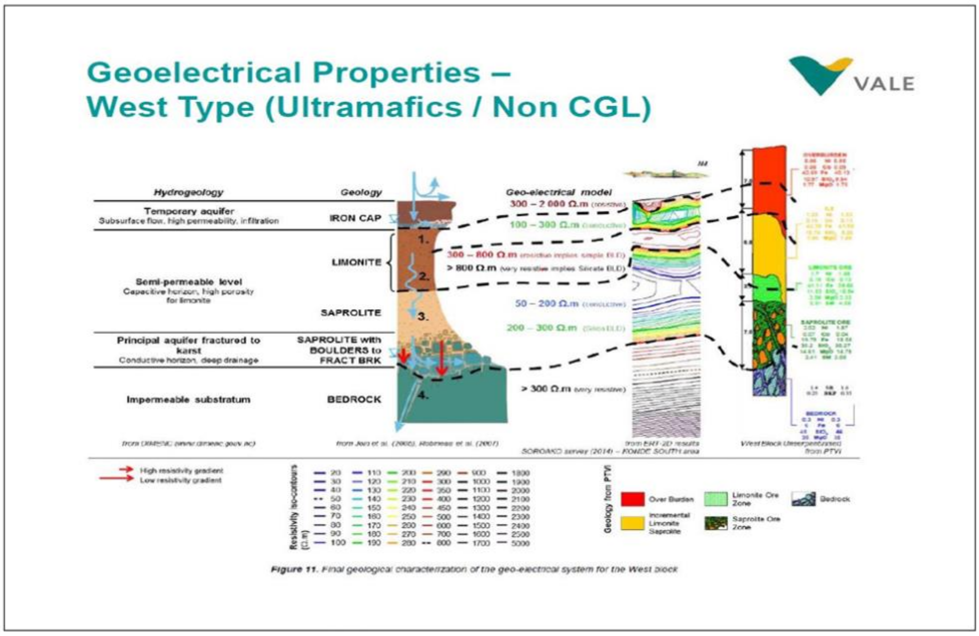
Geoelectrical Properties –
West Type (Ultramafics / Non CGL)

Figure 11. Final geological characterization of the geo-electrical system for the West block

Figure 4 Resistivity characteristics of the West Block area in the research area (PT. Vale Indonesia)

RESULT AND DISCUSSIONS

There are 14 lines, consisting of 7 west-east lines and 7 south-north lines. The tracks have various points that depend on the topographic profile of each line. The total number of boreholes in this study is 102.

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1. Line E02

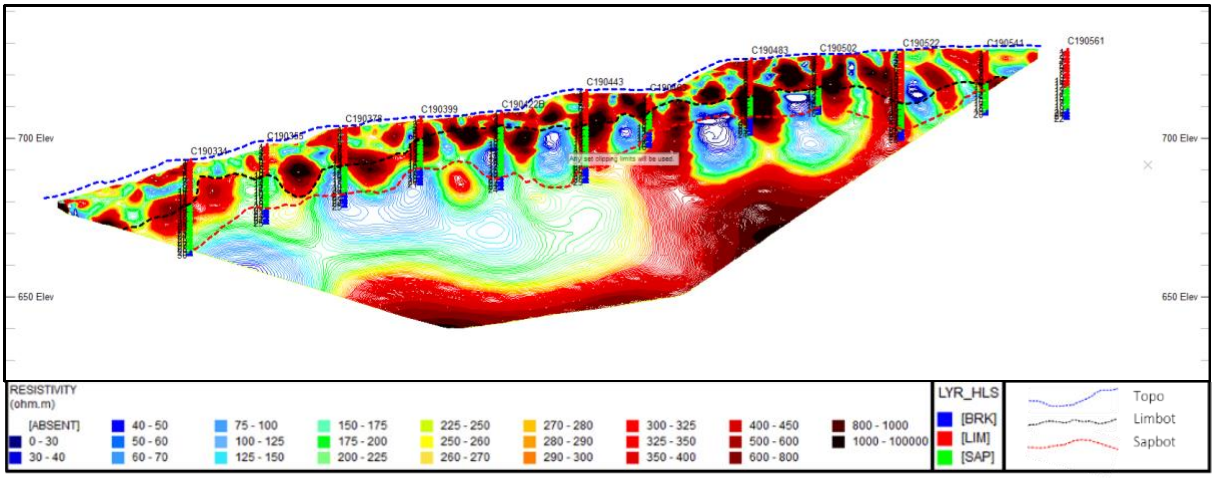

Figure 5 Correlation of resistvity cross-section and drillhole on E02 line

Line E02 stretches north-south over a length of 345 meters. The number of boreholes overlaying the resistivity cross-section is 5, with a spacing of 25 meters between each borehole. Each borehole provides subsurface lithology information based on the collected samples. In the process of interpreting the boundary layers from the resistivity contour patterns, adjustments are made to align with the lithology boundaries indicated by the drillhole data, especially when approaching the drillhole locations.

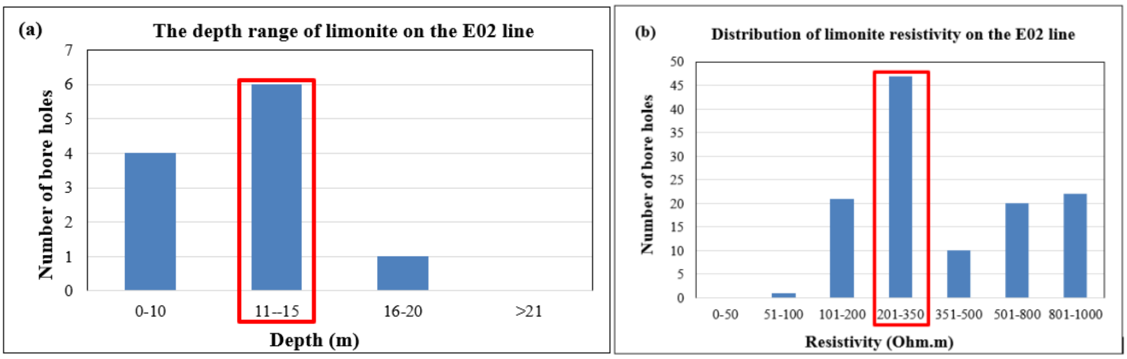

Figure 6 (a) Depth of limonite (b) Resistivity distribution of limonite on the E02 line

Based on the histogram analysis (Figure 6) (a), the depth of limonite is found at 11-15 meters. The resistivity distribution ranges from 201-350 Ohm.m. When observed on the color scale (Figure 5), the resistivity value of 201-350 Ohm.m indicates a medium-high resistivity. According to the borehole data analysis, this corresponds with the fact that limonite contains Fe >40% and has a low SiO_2 content of <5%. The low silica content results in a relatively low resistivity.

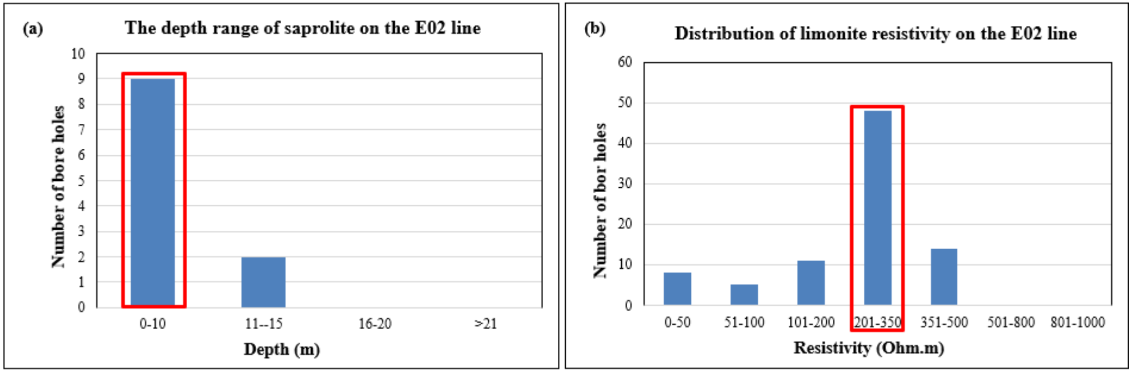

Figure 7 (a) Depth of saprolite (b) Resistivity distribution of limonite on the E02 line

The depth of saprolite obtained from the histogram analysis (Figure 7) (a) is dominant at 0-10 meters. The resistivity distribution of saprolite, as shown in (Figure 7) (b), falls within the same range as limonite, which is 201-350 Ohm.m. As observed in the geochemical appendix, saprolite in the E02 line is rich in silica (SiO_2), which causes its resistivity to resemble that of limonite.

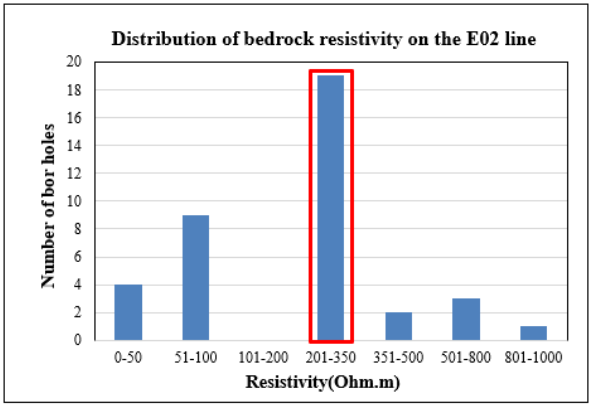

Figure 8 Resistivity distribution of bedrock on the E02 line

The depth of the bedrock zone is assumed to be greater than 15 meters. (Figure 8) shows the resistivity distribution in the bedrock, which ranges from 201-350 Ohm.m. The resistivity value of the bedrock in E02 is relatively low, which is suspected to be due to structural influences that create fractures, allowing fluids to be present within these fractures. This results in the bedrock being conductive.

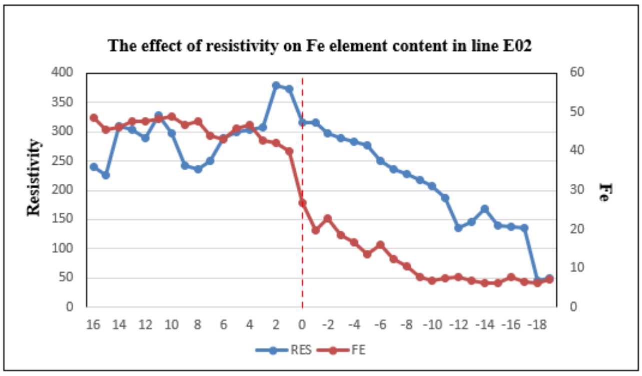

Figure 9 The effect of resistivity on Fe element content in line E02

The graph showing the relationship between Fe content and resistivity values in lateritic nickel indicates a direct proportional relationship. This linear relationship can be seen in the graph (Figure 9), which shows that the limonite layer itself has both high resistivity values and high Fe content. This is due to the lateritic nickel deposition process, where during the formation of lateritic nickel, Fe does not easily dissolve or become mobilized by water movement. Instead, Fe bonds with oxides and precipitates as ferri-hydroxides, accumulating near the ground surface. In the transition zone and saprolite zone, both the resistivity and Fe content begin to decrease significantly until reaching the bedrock layer. Therefore, it can be concluded that Fe is present in large amounts in the limonite layer compared to other layers.

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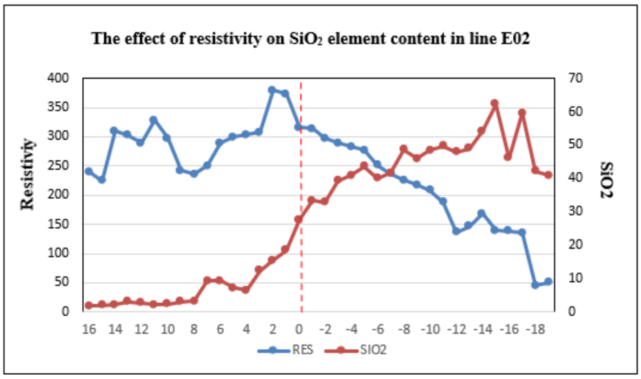

Figure 10 The effect of resistivity on SiO_2 element content in line E02

The graph showing the relationship between SiO_2 content and resistivity values in lateritic nickel demonstrates an inverse proportional relationship. This inverse relationship can be seen in the graph (Figure 10), which shows that the limonite layer has both low resistivity values and low SiO_2 content. This is due to the lateritic nickel deposition process, where SiO_2 is mobilized by water movement along with other elements, unlike Fe, which has already accumulated in the limonite zone. SiO_2 and other elements continue to move downward together as long as water supply to the soil persists. In the transition and saprolite zones, the resistivity increases as SiO_2 content rises significantly. This occurs because SiO_2 remains carried by water into the saprolite zone. In this saprolite zone, SiO_2 undergoes a process of enrichment, where it associates with MgO and Ni. In the bedrock zone, SiO_2 has both high resistivity and high SiO_2 content. Therefore, it can be concluded that the SiO2 content in the saprolite layer is higher than in other layers.

2. Line E04

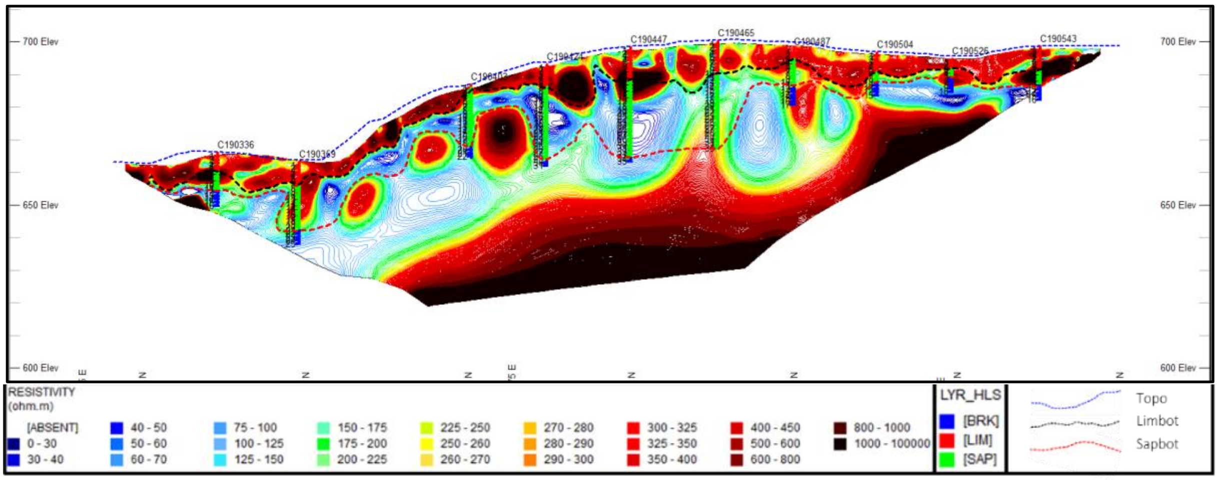

Figure 11 Correlation of resistvity cross-section and drillhole on E04 line

Line E04 stretches north-south over a length of 345 meters. The number of boreholes overlaying the resistivity cross-section is 5, with a spacing of 50 meters between each borehole. Each borehole provides subsurface lithology information based on the collected samples. In the process of interpreting the boundary layers from the resistivity contour patterns, the boundaries will be directed toward the lithology limits indicated by the drillhole data as they approach the borehole locations.

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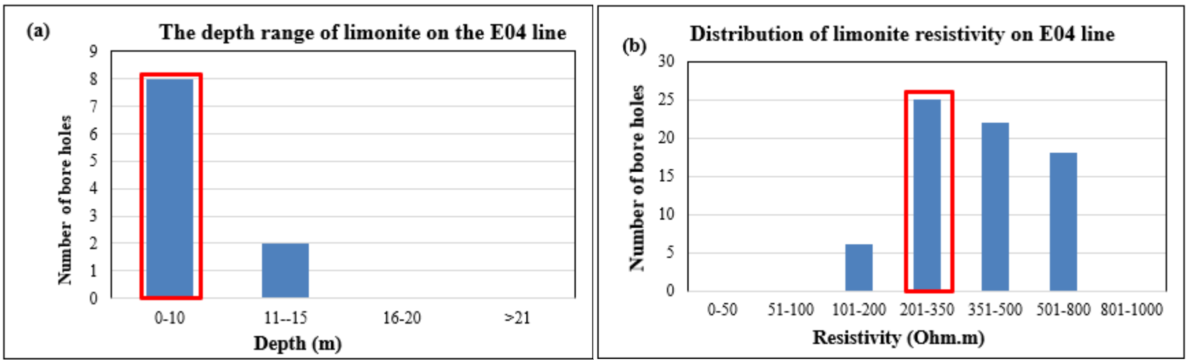


Figure 12 (a) Depth of limonite (b) Resistivity distribution of limonite on the E04 line

Based on the histogram analysis (Figure 12) (a), the depth of limonite is found at 0-10 meters. The resistivity distribution ranges from 201-350 Ohm.m. When observed on the color scale (Figure 11), the resistivity value of 201-350 Ohm.m indicates a medium-high resistivity. According to the borehole data analysis, this corresponds with the fact that limonite contains Fe >40% and has a low SiO_2 content of <5% (Figures 13 & 14). The low silica content results in a relatively low resistivity.

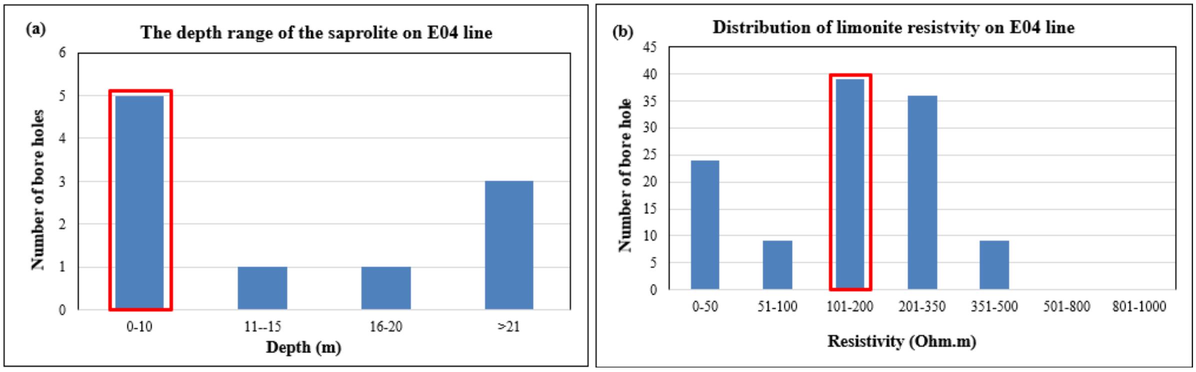


Figure 13 (a) Depth of saprolite (b) Resistivity distribution of saprolite on the E04 line

Based on the histogram analysis (Figure 13) (a), the depth of saprolite is found at 0-10 meters. Its resistivity distribution is slightly lower than that of limonite, ranging from 101-200 Ohm.m. When observed on the color scale, the resistivity value of 101-200 Ohm.m indicates a medium-high resistivity. According to the borehole data analysis, this corresponds with the fact that saprolite contains Fe > 25% and has a high SiO_2 content of >25% (Figures 13 & 14). The high silica content results in high resistivity, which is not much different from limonite.

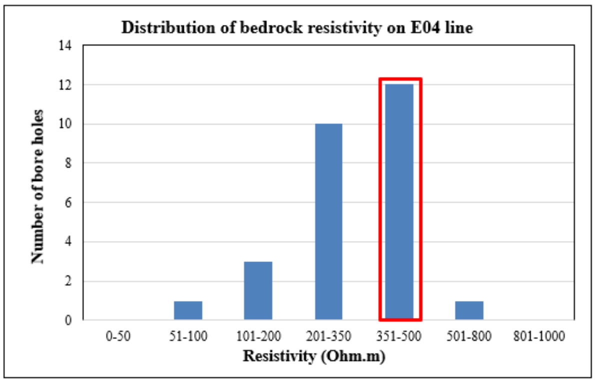


Figure 14. Resistivity distribution of bedrock on the E04 line

Based on the saprolite depth data, the depth of the bedrock is assumed to be greater than 10 meters. The resistivity value, as shown in (Figure 14), is predominantly in the range of 351-500 Ohm.m. This is also observed in the (Appendix), where the lower part of the zone is highly resistive and quite thick, according to the ERT data.

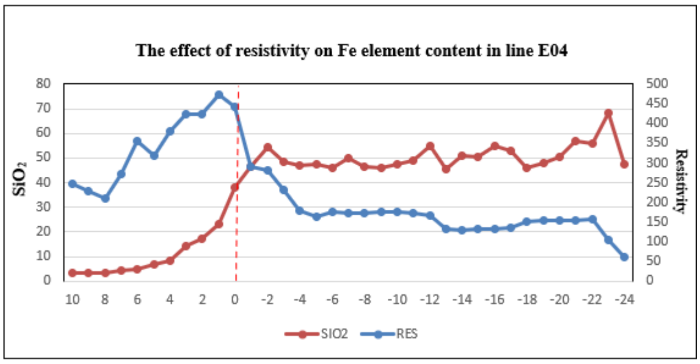


Figure 15. The effect of resistivity on Fe element content in line E02

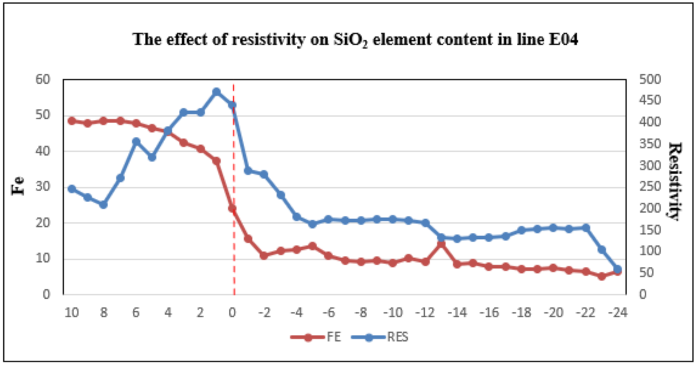


Figure 16. The effect of resistivity on SiO_2 element content in line E02

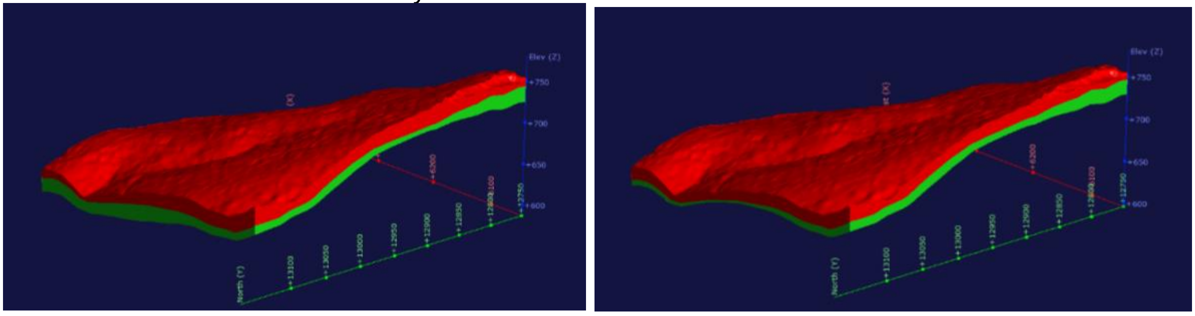
The influence of resistivity on Fe and SiO_2 elements in the E04 line is similar to other lines, where resistivity shows a direct proportional relationship with Fe and an inverse proportional relationship with SiO_2.

The depth analysis of each line shows that the limonite and saprolite layers are found at 0-10 meters. According to the ERT results, the boundary between saprolite and bedrock is difficult to distinguish. Based on the available borehole data, this is suspected to be due to fractures in the bedrock. These fractures allow fluids to easily infiltrate, making weathering more prominent in fractured areas. The fluid filling the fractures in the bedrock causes a low resistivity response. As a result, ERT has difficulty distinguishing between water-saturated saprolite and bedrock filled with fluid.

Based on the ERT analysis, the resistivity distribution of limonite is predominantly in the range of 201-350 Ohm.m across all ERT lines. The resistivity distribution for saprolite is predominantly in the range of 101-200 Ohm.m, which is relatively high for water-saturated areas. This is because saprolite is rich in silica. The resistivity distribution of the bedrock varies between 101 and more than 801 Ohm.m. The low resistivity values in the bedrock are suspected to be due to the fluid filling the fractures.

Geological Model

(Figure 17) shows the geological modeling of limonite and saprolite based on the interpretation of the correlation between resistivity values and drillholes.



(a) (b)

Figure 17 (a) 3D view of limonite and saprolite volumes interpreted based on correlation of resistivity and drillhole values (b) 3D view of geological modelling of limonite and saprolite interpreted based on drillhole

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In (Figure 17 (a)) above, the 3D geological modeling of limonite and saprolite follows the boundaries that have been established. The red color represents the limonite zone, while the green color represents the saprolite zone. It can be observed that the cross-section produced from the interpretation of the correlation between resistivity values and drillholes tends to be wavy and erratic. This is because the interpretation process or the determination of the limonite bottom and saprolite bottom boundaries is done by following the contour pattern generated from the resistivity values.

In (Figure 17 (b)), it can be seen that the cross-section produced based on the drillhole-to-drillhole interpretation is relatively more rigid or flat. This is because the interpretation process or the determination of the limonite bottom and saprolite bottom boundaries is done by drawing straight lines between drillholes based on the lithology information available.

Below is a comparison table of the volumes produced from the two parameters, namely the interpretation based on the correlation between resistivity values and drillholes (ERT) and the drillhole-to-drillhole interpretation.

Table 1. Comparison of ERT and drillhole volumes

Domain	ERT and drillhole volume (m^3)	Drillhole volume (m^3)	Percentage difference
LIM	1.625.300	1.523.100	6%
SAP	1.902.600	1.390.100	27%

Table 1 shows that the volume of limonite generated from the correlation between drillholes and resistivity (ERT) is larger compared to the drillhole-to-drillhole interpretation, with a percentage difference of 6%. For saprolite, the volume generated from the correlation between drillholes and resistivity (ERT) is also larger than the drillhole-to-drillhole interpretation, with a percentage difference of 27%. The overall volume difference shows that the volume generated from the correlation between drillholes and resistivity is larger, amounting to 614,700 m^3, which represents a 17% difference.

Comparison Analysis

In this study, a comparison was made between the geometry of the limonite and saprolite boundaries generated from the interpretation of the correlation between drillholes and resistivity (ERT) and the drillhole-to-drillhole interpretation. Below is one example of an ERT cross-section overlayed with the drillhole data to observe the differences produced.

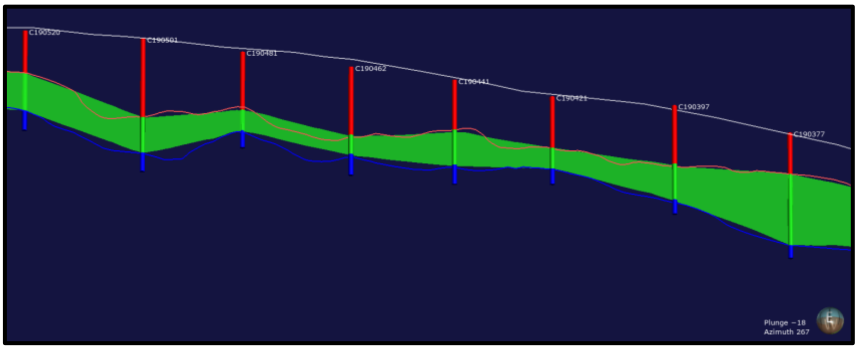

Figure 18 ERT and drillhole volume cross-section overlay

Based on (Figure 18), the green area represents the saprolite zone according to the drillhole interpretation, while the white line represents the topography, and the red and blue lines indicate the top and bottom boundaries of the saprolite zone based on ERT. From this image, it can be seen that there is a difference in the boundary interpretations produced by drillhole and ERT. This is because the bottom boundaries of limonite and saprolite based on the drillhole interpretation are drawn by connecting straight lines between one drillhole and another, while the boundaries drawn based on ERT follow the contour patterns, resulting in a more erratic shape. For a clearer view, refer to (Figure 19).

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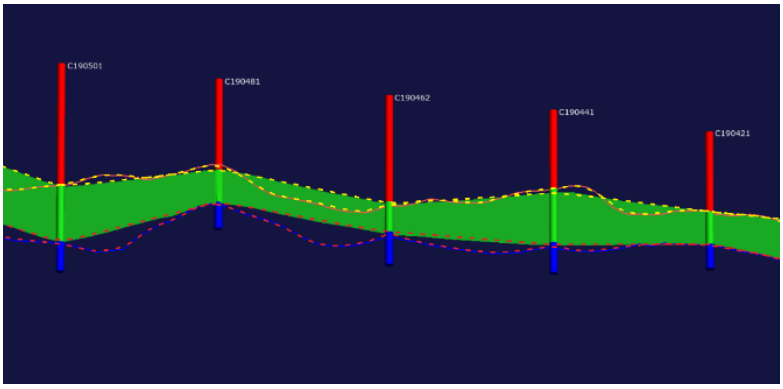

Figure 19 Difference between ERT and drillhole volume cross-section

From (Figure 19) above, it can be observed that there are areas identified by the drillhole as saprolite, but based on the ERT, these areas are classified as bedrock. Additionally, there are areas identified as limonite by the drillhole, but based on the ERT, these areas are classified as saprolite. These areas, marked by shading, indicate discrepancies between the two different interpretation parameters.

CONCLUSION

Based on the data analysis conducted in the study area, the following conclusions can be drawn:

1. The boundaries of the lateritic nickel layers based on resistivity and borehole data are:
    - Limonite: A soil layer rich in goethite, a product of weathering. This material has high porosity and permeability. The resistivity value is moderate to high, ranging from 201-350 Ohm.m.
    - Saprolite: A soil layer with low permeability that is water-saturated. It serves as a site for supergene enrichment, containing high amounts of lateritic nickel. The resistivity value is slightly lower, ranging from 101-200 Ohm.m.
    - Bedrock: The parent rock that has not undergone weathering. The rock remains massive. The resistivity response is high, ranging from 101 to >801 Ohm.m.
2. The presence of silica minerals causes the resistivity response to be high. In the study area, the saprolite zone is dominated by silica-rich saprolite. Its resistivity response tends to be high, approaching the resistivity of the limonite zone. Fractures in the bedrock can accelerate weathering in the bedrock. These fractures become filled with fluids, which act as a factor to speed up weathering. This fluid causes the resistivity value to be relatively low. The low resistivity response in the bedrock of the study area is interpreted as a result of fractures filled with fluid.
3. The volume of the geological model based on the boundary interpretation of the resistivity and drillhole correlation is 1,625,300 m^3 for limonite and 1,902,600 m^3 for saprolite. Meanwhile, the reserves generated based on the drillhole-to-drillhole interpretation are 1,523,100 m^3 for limonite and 1,390,100 m^3 for saprolite. The percentage difference in reserves is 6% for limonite and 27% for saprolite.

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REFERENCE

Ahmad, W. (2002*).Nickel laterites-A Short Course : Chemistry, Mineralogy and Formation of Nickel Laterites*. Unpublished

Lisensi**:** cc-by-sa

Ahmad, W. (2002).*Laterites- Fundamentals of chemistry, mineralogy, weathering, proses and laterite formation*. Unpublished

Ahmad, W. 2006. *Laterite : Mine Geology at PT. International Nickel Indonesia. Sorowako*. Unpublished

Ahmad, W. (2009).*Nickel laterites-A Short Course : Chemistry, Mineralogy and Formation of Nickel Laterites*. Unpublished

Boldt, J.R. (1967). *The Winning of Nickel, The Hunter Rose Company*. Longmans, Canada.

Bankes. 2003 . *Estimation of mineral resources and mineral reserves best practice guidelines*. Ensiklopedi Pertambangan Edisi 3, Puslitbang Teknologi Mineral.

Darijanto, Totok. (1986). "*Pengaruh morfologi terhadap pembentukan dan penyebaran nikel lateritik.*

Elias M. (2002). *Nickel laterite deposits – geologic overview, resources and exploitation in Giant ore Deposits: characteristics, genesis, and exploration, Cooke, D.R., Pongratz, J.,eds Centre for ore deposits research. special Publication 4*. University of Tasmania, P 205-220,.

Evans, A.M. (1993). *Ore Geology and Industrial Minerals*. Blackwell Scientific Publications, Oxford, p 390.

Fitrian, E. B. (2021). Identifikasi Sebaran Nikel Laterit dan Cadangan Bijih Nikel Menggunakan Korelasi Data Bor. *Paulus Civil Engineering Journal, 3*, 113-119.

Golightly, J. P.1979. *Geology of Soroako nickeliferous laterite deposit*. INCO Metals Company, Ontario: Canada.

Golightly, J. P. 1981. *Nickeliferous Laterite Deposits*. Economic Geology (75th Anniv.), pp. 710-735

Hamilton, W. (1979). *Tectonics of Indonesian region*. United States Government Printing Office. Washington.

Kumarawarman, B. 2016. *Engineering Geology Of Sorowako and Petea*. (PT. Vale Indonesia Tbk.)

Looke, M.H. 2004. Tutorial: 2-D and 3-D Electrical Imaging Surveys. *Geotomo Software.* Penang, Malaysia.

Lowrie, W. 2007. Second Edition: *Fundamentals of Geophysics*. Cambridge University Press: Cambridge.

Maulana Adi. (2017). *Endapan Mineral*. Penerbit Ombak 2017: Yogyakarta

Pearl, R,M. (1988). *Geology, 4th Edition, A Division of Harper Amd Row*. Publisher, New York, Hagerstown, San Francisco, London

Ringwood, A.E., 1975. *Composition and Petrology Of The Earth's Mantle*. McGraw-Hill, Inc: New York.

Simandjuntak, T.O., 1986, *Sedimentology and Tectonics of the Collision Complex in the East Arm of Sulawesi*, Unpub. PhD thesis RHBNC University of London, 374 pp

Simandjuntak, T.O., Rusmana, E., Surono dan Supandjono, J.B. 1991. *Geologi Lembar Malili, Sulawesi*. Departemen Pertambangan dan Energi, Direktorat Jenderal Geologi Dan Sumber Daya Mineral, Pusat Penelitian Dan Pengembangan.

Simanjuntak, T.O. 1993. *Neogene Plate Convergence in Eastern Sulawesi*.Jurnal Geologi dan Sumberdaya Mineral, no. 25 v.VIII, hal. 2-15.

Simandjuntak, T.O., Rusmana, E., Surono dan Supandjono, J.B. 1994. *Geologi Lembar Bungku, Sulawesi*. Departemen Pertambangan dan Energi, Direktorat Jenderal Geologi Dan Sumber Daya Mineral, Pusat Penelitian Dan Pengembangan.

Sukamto, R. 1975. *Geologi Sulawesi*. Departemen Pertambangan dan Energi, Direktorat Jenderal Geologi Dan Sumber Daya Mineral, Pusat Penelitian Dan Pengembangan.

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). *Applied geophysics*. Cambridge university press.

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