Engineering and Technology Journal e-ISSN: 2456-3358

Volume 09 Issue 08 August-2024, Page No.- 4871-4877

DOI: 10.47191/etj/v9i08.36, I.F. – 8.227

Delineation of Nickel Laterite Deposits Based on Geoelectric Method in Area "X", Southeast Sulawesi, Indonesia

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ABSTRACT: Sustainable nickel exploration is urgently needed as the demand for nickel in Indonesia increases. Area "X" Southeast Sulawesi, Indonesia, is one of the nickel producer areas in Indonesia. A geophysical exploration method that can effectively and efficiently increase the discovery of laterite nickel potential is the Electrical Resistivity Tomography (ERT) or the resistivity geoelectric method. ERT measurements in the study area were carried out to see the potential of nickel laterite deposits that can be mined. ERT measurements were carried out as many as 6 lines, and there was drill data as many as 5 drill points in the study area. Data processing of resistivity values using Res2DInv software, then made resistivity cross-section, lithology cross-section, resistivity cross-section vs. drill data, correlation of paths, depth slicing map, and 3D modeling for each layer of nickel laterite. The results showed that the study area contained limonite, saprolite, saprock, and bedrock layers. The resistivity value in the limonite layer is (61 – 150) Ohm.m, the saprolite layer is (1 – 60) Ohm.m, the saprock layer is (61 – 150) Ohm.m, and the bedrock layer has a resistivity value of more than 150 Ohm.m. The distribution of nickel laterite deposits consisting of limonite, saprolite, and saprock in the study area is thicker to the east. Nickel laterite deposits in the eastern zone have a thickness of about 60 meters, while in the western zone, it has a thickness of about 10 meters. This is due to the indication of a southwest-northeast oriented fault, so the western zone has a higher morphology than the eastern zone.

KEYWORDS: nickel laterite deposits, resistivity, modeling, dipole-dipole configuration, exploration

I. INTRODUCTION

International trade is a very important for a country because it supports economic prosperity. International trade brings many benefits, especially for developing countries like Indonesia. Indonesia is a country that is blessed with abundant natural resources. Indonesia's abundant natural resources can be an opportunity to market them globally. Indonesia ranks first as the world's largest nickel-producing country and managed to book nickel production of up to 1.6 million metric tons in 2022 and contributed around 48.48 percent of the world's nickel (USGS 2023). Nickel resources can be found in two forms, namely primary nickel and secondary nickel. Indonesia only finds nickel in the form of secondary nickel commonly called laterite nickel (Isjudarto 2013).

A geophysical exploration method that can effectively and efficiently improve the discovery of nickel laterite reserves is the Electrical Resistivity Tomography (ERT) method or often known as the resistivity geoelectric method. The ERT method is one of the methods used to determine the characteristics or resistivity value of the nickel laterite profile. The research was conducted in area "X," Southeast Sulawesi, with a dipole-dipole configuration.

A study using the ERT method with dipole-dipole configuration was conducted in Southeast Sulawesi. The laterite nickel deposit model in the study area consists of a limonite zone, saprolite zone, saprock, and bedrock. Flatter topography produced thicker nickel laterite deposits than steeper topography (Santoso and Subagio 2018). A study using the ERT method with the Wenner configuration was also conducted in North Kolaka, Southeast Sulawesi. The thickness of nickel laterite deposits is influenced by morphology, which is one factor that plays a role in the weathering and leaching process (Santoso, Wijatmoko, and Supriyana 2017). In relatively gentle slope conditions, the nickel content in the limonite zone is 1.99% and 2.13% in the saprolite zone. Otherwise, the nickel content in steep areas is lower, which is 1.01% in limonite and 1.46% in saprolite (Hasria et al. 2024). North Konawe has steep slopes, high levels of rock weathering, cracked and loose rocks, including fault lines, road-cut slopes, and routine vehicle vibration (Umar et al. 2019).

The purpose of this study is to define the lithology of the nickel laterite deposits layer based on the resistivity value, determine the distribution of resistivity values, and to make an model to see the distribution of nickel laterite deposits layer. The 2D ERT data processing in this study using Res2Dinv software to make a resistivity section. Res2Dinv software processing results will be correlated with supporting data in the form of drill data. The distribution of nickel laterite deposits in the research area is known by the outputs such as resistivity cross section correlation, depth slicing map, and 3D modeling.

A. Geology of the Study Area

The location of the study is in the Ophiolite Complex of the Southeast Arm of Sulawesi, which is part of the East Sulawesi Ophiolite Range. Figure 1 is a geological map of the Southeast Arm of Sulawesi.

Based on the Regional Geological Map of Lasusua-Kendari Sheet, Sulawesi, the lithology in the study area is alluvial surface deposits and ultramafic igneous rock groups that contain dunite, harzburgite, lherzolite, peridotite, pyroxenite, and serpentinite. The regional stratigraphy of the Southeast Arm of Sulawesi is shown in Figure 2.

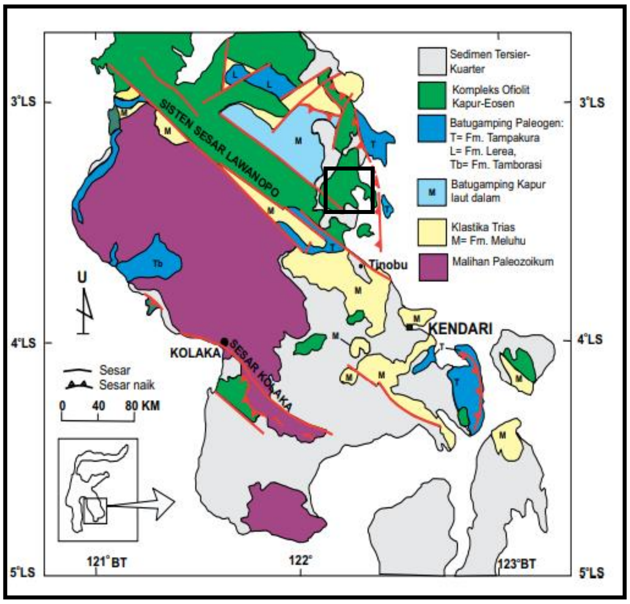


Figure 1. The geological map of the Southeast Arm of Sulawesi (Surono 2013), the study area is shown by a black square.

The Southeast Sulawesi region structures were formed during the collision and post-collision phases. The collision between continental pieces and ophiolites resulted in various geological structures, such as thrust faults, imbrication structures, and folds (Surono 2013). Rising faults generally form the boundary between the ophiolite and the continental slice of Southeast Sulawesi. Rising faults form imbrication zones that are visible along the east and west coasts of the Southeast Sulawesi Arm.

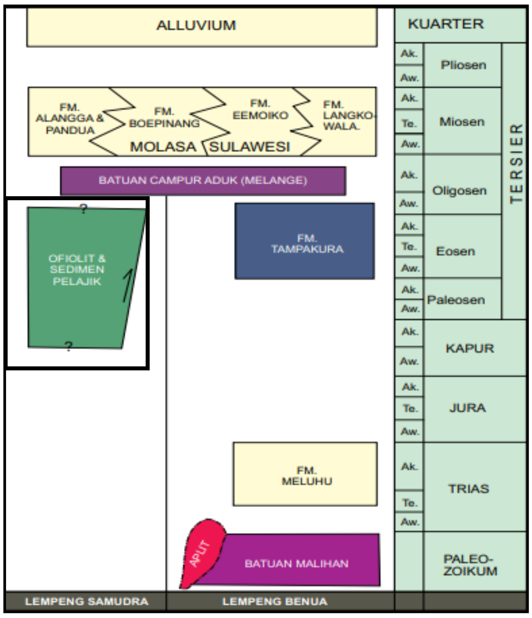
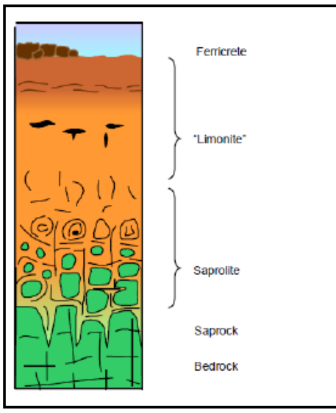


Figure 2. Regional stratigraphy of the Southeast Arm of Sulawesi (Surono 2013), the study area is shown by a black square.

B. Nickel Laterite

Nickel laterite is a product of ultramafic rocks' chemical and physical weathering and enrichment. Weathering is the physical and chemical changes of rocks or minerals near or on the earth's surface. Physical and chemical changes in ultramafic rocks accompanied by the laterization process produce an economic laterite deposit (Ahmad 2006). The laterite nickel profile is shown in Figure 3.



Fe	MgO	Ni	Co
>50%	<0.5%	<0.6%	<0.1%
40-50%	0.5-5%	0.8-1.5%	0.1-0.2%
10-25%	15-35%	1.5-3%	0.02-0.1%
5%	35-45%	0.3%	0.01%

Figure 3. Profile of nickel laterite deposit (Elias 2002)

Some of the ultramafic rocks commonly found are dunite, harzbugite and peridotite.The lateritization process lasts for millions of years begins when ultramafic rocks are exposed on the earth's surface until they produce nickel residues (Surono 2013).

II. RESEARCH METHODS

Area "X", Southeast Sulawesi, is an area that is under exploration, so there are already no active mines. The study used 2D ERT secondary data with a dipole-dipole configuration. ERT measurements were carried out on six lines with five drill points as shown in Figure 4.

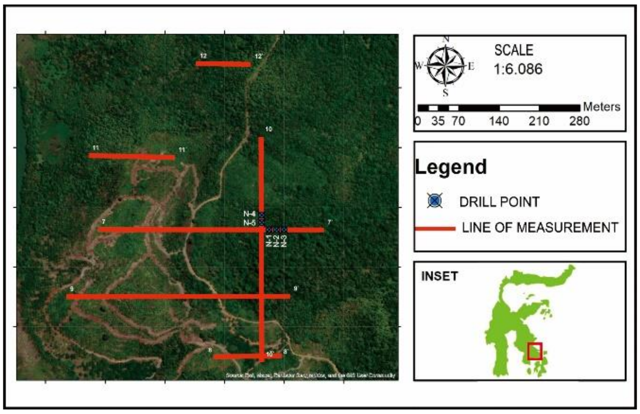


Figure 4. Design survey map of the study area.

The tools and equipment used in ERT data acquisition in the research area include machetes, electrode connectors, main units, cables that connect electrodes and main units, batteries, HT, electrodes, GPS, and cables that connect main units and batteries.

The raw data acquired from the resistivity method is directly from the tool in .bin format, so they must be converted into .dat format using Prosys II software and then transferred to Notepad. The data processing needs several software such as Res2Dinv, Oasis Montaj, Rockwork, Leapfrog, Surfer, and Coreldraw.

The resistivity method is based on the assumption that the earth has isotropic homogeneous properties. The measured resistivity is the true resistivity, and it doesn't depend on the electrode spacing. However, in reality, the earth is composed of layers with different resistivities, so these layers influence the measured potential. The measured resistivity value is the resistivity value for one layer only. The measured resistivity is the apparent resistivity (ρa) (Reynolds 2011). The apparent resistivity is formulated:

$$\rho_a = K\frac{\Delta V}{I} \qquad (1)$$

Where ρa is apparent resistivity (Ωm), K is geometry factor, ΔV is potential difference (V), and I is current strength (A). The inversion process is carried out to convert the apparent resistivity value into the actual resistivity value.

The dipole-dipole configuration geoelectric method uses two current electrodes and two voltage electrodes injected into the underground. The distance between the current electrode and the voltage electrode is nx while the distance or space between each electrode is the same, namely a (distance C1C2 = distance P1P2 = x), as shown in Figure 5.

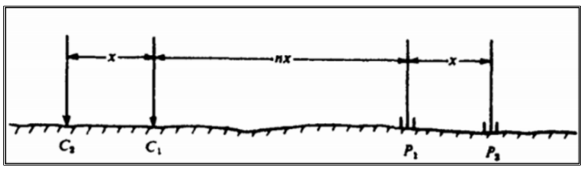


Figure 5. Current and potential electrodes in dipole-dipole configuration (Telford, Geldart, and Sheriff 1990)

Different arrangements of current electrodes and voltage electrodes may also lead to the use of different geometry factors (K). The dipole-dipole configurations, a geometry factor is used (2):

$$K = \pi n(n+1)(n+2)a \qquad (2)$$

III. RESULT AND ANALYSIS

The results of Res2Dinv software processing produce inversion values on each line from 0.99 to 6696.6 Ohm.m. The resistivity value in the inversion results is analyzed for its distribution, so it results in the division of the resistivity value range shown in the classification table as table 1.

Low resistivity values are indicated as saprolite layers, medium resistivity values are indicated as limonite layers when near the surface or saprock (saprolite rock) layers when between saprolite and bedrock, and high resistivity values are indicated as bedrock layers.

Table 1. Classification of resistivity values of nickel laterite deposits in the study area

No	Category	Resistivity (Ohm.m)	Interpretation
1	Low	1 – 60	Saprolite
2	Medium	61 - 150	Limonite or Saprolite Rock
3	High	>150	Bedrock

The profile of nickel laterite deposits in the study area is divided into four layers, which are limonite layer, saprolite layer, saprock layer and bedrock layer. Fe abundance in the limonite zone decreases gradually from the limonite zone to the bedrock. Fe and Al elements with immobile elemental mobility make these minerals have a higher resistance to weathering, so their presence is concentrated in the upper part of laterite deposits (Ramadhani, Cahyadi, and Handayani 2023). Limonite is generally located near the surface and contains ultramafic rock building materials and resistive silica of gravel-boulder size. The characteristics of the limonite layer when the current is applied are highly resistive, hard and dense, high in iron and low in water, soft and porous, and similar to homogeneous soil (Salsabila 2021). The limonite layer has much vegetation, making the ground surface have many air cavities, resulting in a higher resistivity value than the layer above it.

Saprolite has a high porosity due to the weathering process, allowing water to fill in and impact the resulting resistivity value. The saprolite layer chemically contains a lot of magnesium (Mg) and nickel (Ni) elements and reduced iron (Fe) elements, which are found in the limonite layer zone (Fitrian 2021). The characteristics of the saprolite layer when the current is electrified are moderately conductive, have low porosity, a hard texture like clay, and high water content, so the resistivity value produced is lower than other layers (Nabila, Anda, and Haraty 2020).

The saprolite layer contains a layer of saprolite rock (saprock).The saprock layer is above the bedrock.The saprock layer is a transition area between the saprolite layer and the bedrock zone, so it will mostly have the properties of the saprolite layer and the bedrock zone together.The characteristics of saprolite boulders are resistive boulders but with conductive weathered skin, low water content (Nabila, Anda, and Haraty 2020).

The high resistivity value is interpreted as edrock of the peridotite rock type.This layer is composed of major minerals such as olivine and pyroxene, with relatively low Ni content (Okto et al. 2023). This bedrock has not been weathered and the density and hardness of the material is very high.

A. Resistivity Section

Figure 5 is the result of the resistivity section and lithology section on the L7 lines that is west to east. The length of the L7 lines is 940 meters. The L7 resistivity section has passed iteration 5 times and the RMS error value is 16.5%.

The limonite layer on L7 has a thickness of about 5 meters at (0 – 200) meters and (350 – 480) meters, the saprolite layer has a thickness of up to 50 meters, and the saprock layer has a thickness of up to 20 meters. The fault is indicated at 320 meters from the starting point of the traverse. The fault is depicted with a dashed black line. The faults cause the nickel laterite deposits, which are composed of limonite, saprolite and saprock in the western zone to be thinner than the eastern zone. The steep and rugged morphology of the study area can cause differences in the thickness and distribution of nickel laterite deposits. The interpretation of nickel laterite deposits is supported by drill data available in the study area. Figure 6 is one of the drill data available in the study area.

The inline borehole on line L7, N-1 has a top soil layer located at (0 - 0.5) meters, a saprolite layer of (0.5 – 14) meters, and a bedrock layer which is peridotite rock is found at (14 – 17) meters. Bedrock suspected by drillers in the field needs further chemical analysis because drillers stop drilling when they reach hard rock with a thickness of more than 3 meters. The field interpretation of suspected bedrock is in fact saprolite rock found at the saprolite bottom.

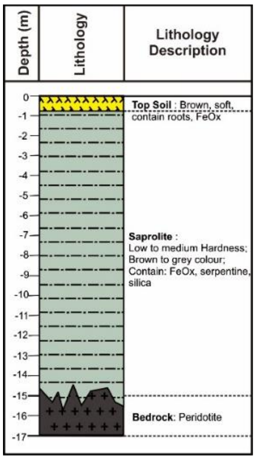
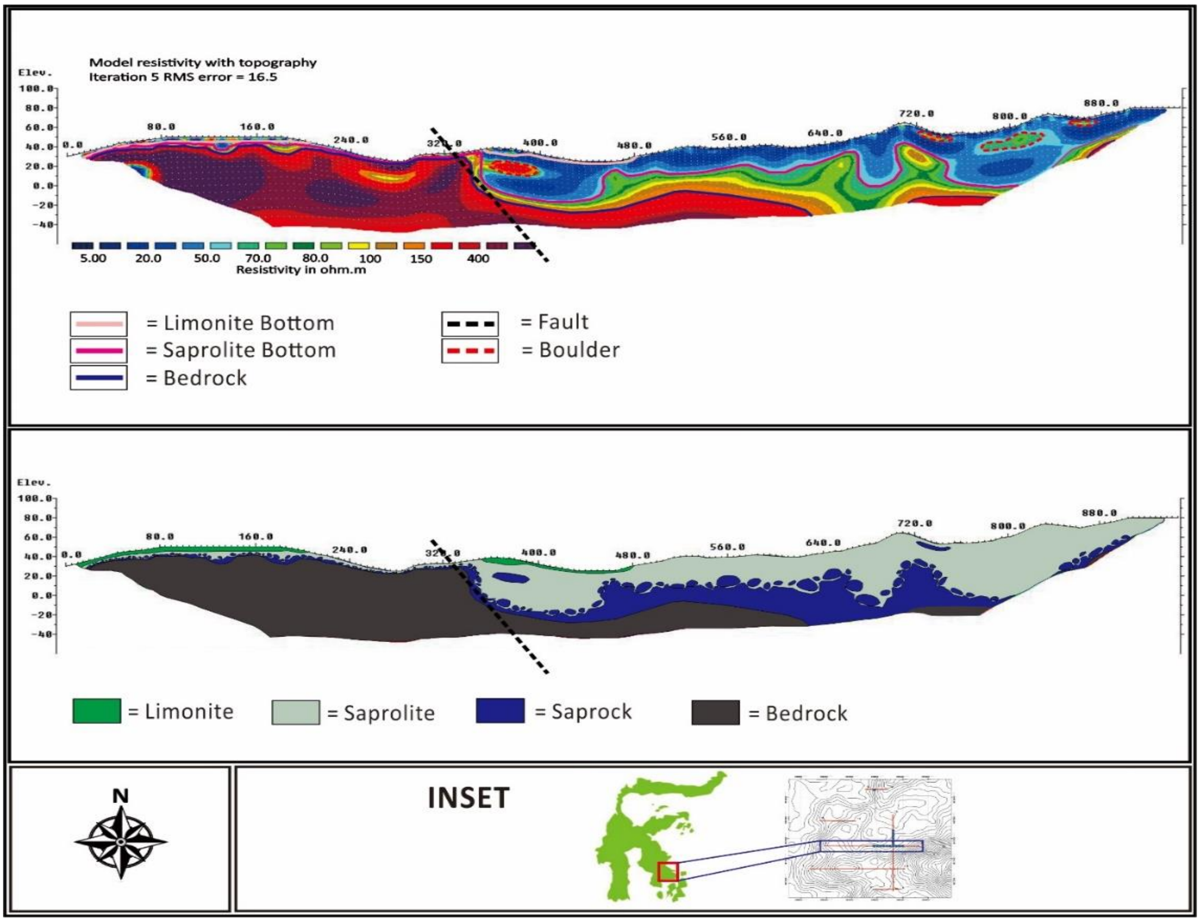


Figure 6. Lithologic section from the drill core, e.g. drill point N-1



B. Resistivity Section Corrlatioon

Correlation of all resistivity section paths used to facilitate interpretation and show the combined resistivity section of the six paths. The correlation is shown in Figure 8.

The stand out response from all sections is the presence of faults on the L7, L8, and L9 sections, so that the western zone in the study area has a thinner laterite layer than the eastern zone. The response is an indication of geological structure in the form of faults. The fault is characterized by a black dashed line.

The weathering process in ultramafic igneous rocks can be in the form of physical weathering and chemical weathering. Physical weathering can be caused by geological structures in the form of faults that occur in the study area. The presence offaults can cause cracks in the rock so that it can accelerate weathering. This is likely to occur in the eastern zone so that the zone has a much thicker layer of nickel laterite deposits than the western zone.

C. Depth Slicing

In figure 9, the slicing map of (-3.8) meters depth is the result of resistivity values that are as far as 3.8 meters below the surface. This map is dominated by the saprolite layer which is shown in blue. The limonite layer in the research area has a thickness of (0 – 5) meters. The slicing map at a depth of (-3.8) meters shows the presence of a limonite layer related to the thickness of nickel laterite because the depth slicing map shows that the western part of the study area has thicker bedrock than the western part of the study area. research area has thicker bedrock than the eastern - southeastern part of the research area.

The suspected fault is strengthened because the resistivity value response at a certain depth shows the same results. When viewed from its continuity, the fault has a southwest-northeast direction, so it appears that the western part of the research area has a thinner layer of nickel laterite deposits than the layer of nickel laterite deposits in the eastern area. Nickel laterite deposits are thinner than those in the east.

Traces that show layer boundaries strengthen the interpretation of faults in the study area. The fault is visible up to a depth of -43.0 meters. The distribution pattern of nickel laterite deposits thickens towards the east of the study area.

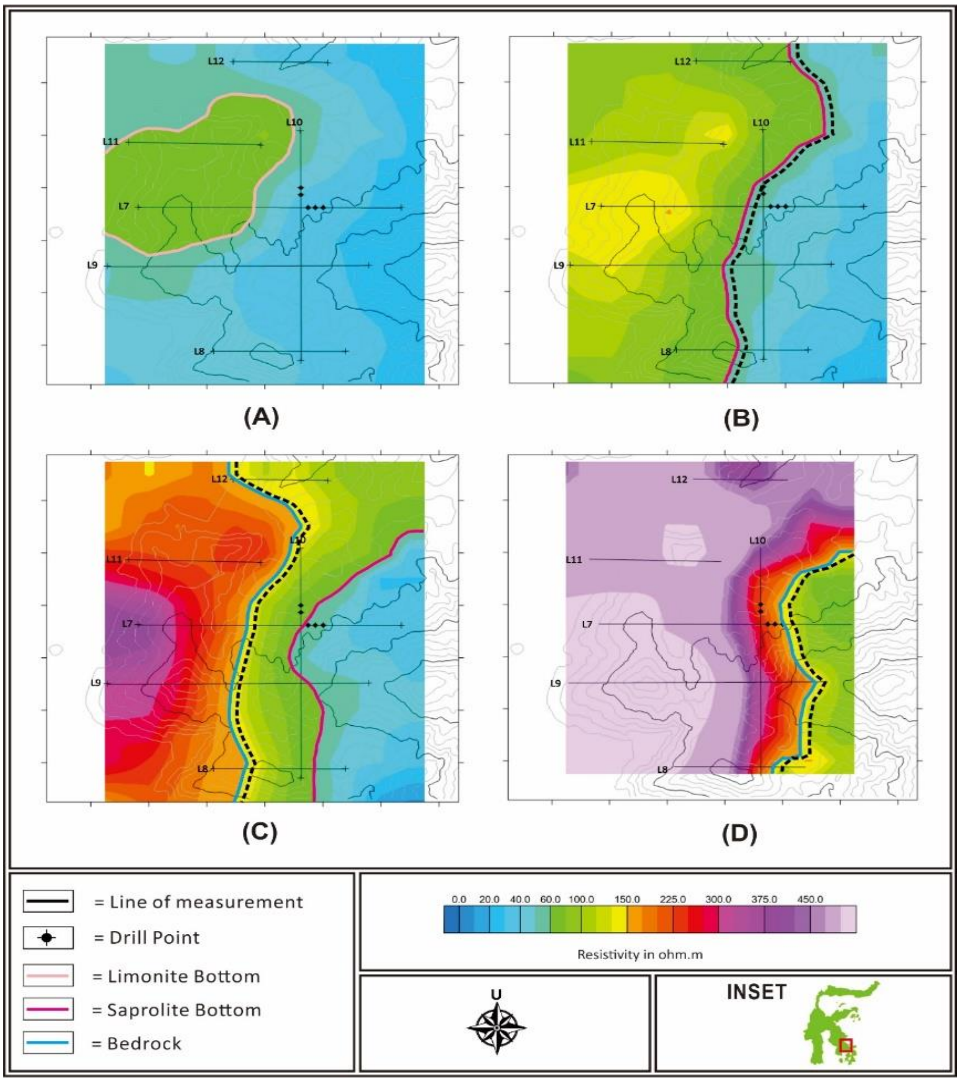


Figure 9. Slicing map at depth (a) -3,8 m; (b) -6,7 m; (c) 9,9 m; (d) 43 m.

D. 3D Modeling

The geology of the study area dominated by ultramafic rocks, allows for more lateritic nickel deposits to be formed. The limonite layer of the study area has a thickness of up to 5 meters. The saprolite and saprock layers in the study area have the thickest thickness among other layers. This layer has the potential for nickel laterite mining because of the high nickel content.

The saprolite layer is a mixture of rock remnants, passive, formed from a transition zone from limonite to bedrock so that the structure and texture of the original rock are still visible. The saprolite layer is a mixture of rock remnants, passive, formed from a transition zone from limonite to bedrock so that the structure and texture of the original rock are still visible. The nickel content in the saprolite layer is greater than in the limonite layer, which is 1.5% - 4% (Elias 2002), , while the iron content is lower than the limonite layer, so the saprolite layer is also a target in laterite nickel mining.

The deepest part of nickel laterite deposits is bedrock which is composed of chunks or blocks of parent rock which generally does not contain economic minerals (the level is close to or equal to the bedrock), namely nickel content of 0.3% and iron content of 35% - 45% (Elias 2002). Therefore, the depth of the bedrock needs to be known to determine the limit of nickel laterite mining.

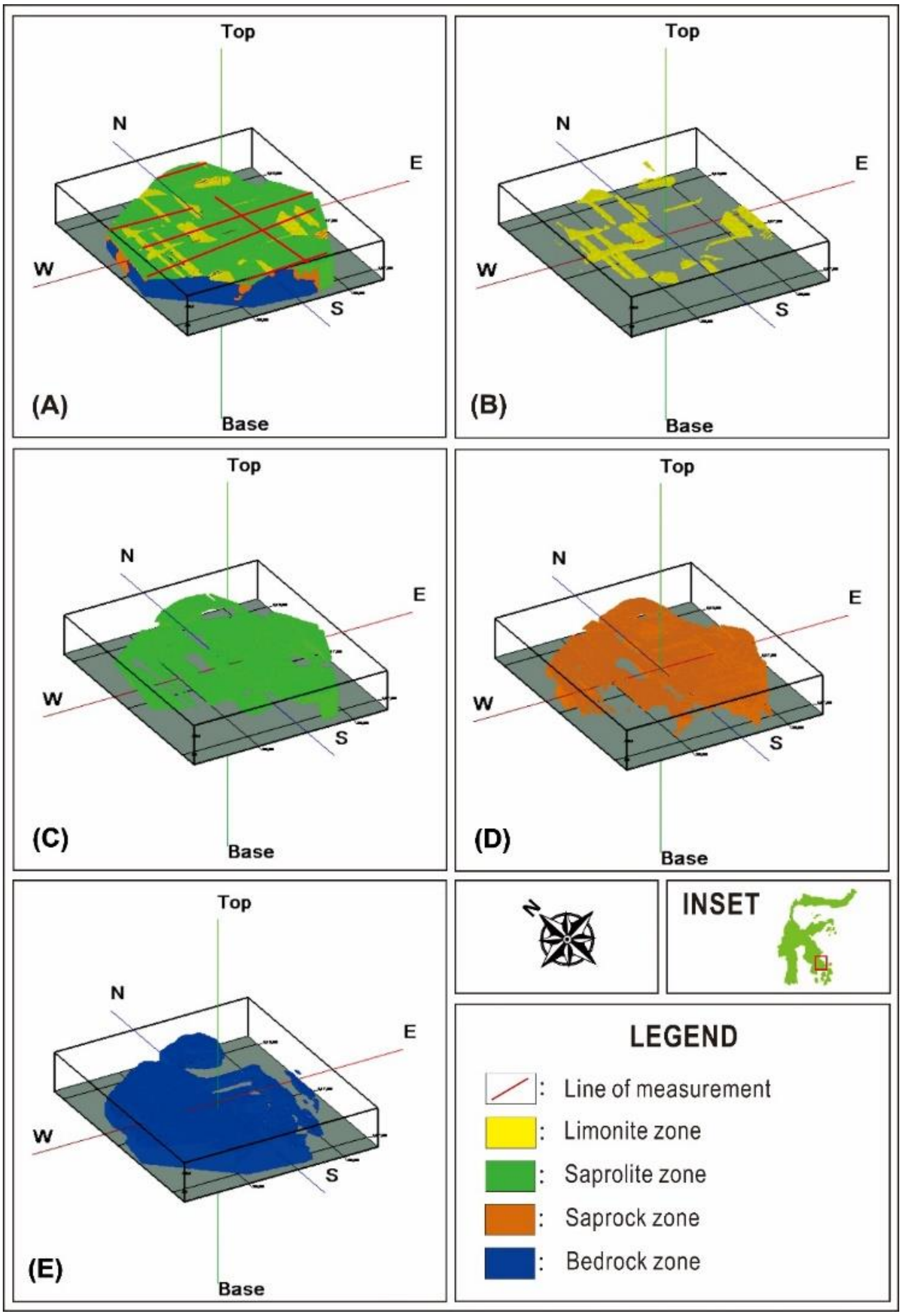


Figure 10. (a) 3D model of laterite nickel deposits; (b) 3D model of limonite layer distribution; (c) 3D model of saprolite layer distribution; (d) 3D model of saprock distribution; (e) 3D model of bedrock distribution.

CONCLUSIONS

The results show that in the research area, there are layers of limonite, saprolite, saprock, and bedrock. The resistivity value in the saprolite layer is (1 – 60) Ohm.m, the limonite layer and saprock layer are (61 – 150) Ohm.m, and the bedrock layer has a resistivity value of more than 150 Ohm.m. The limonite layer in the study area has a thickness of (0 – 5) meters due to morphological factors in the study area. The saprolite layer contains the highest Ni content, in the research area, it is scattered on all tracks with a thickness ranging from (5 – 50) meters. The layers of nickel laterite deposits consisting of limonite, saprolite, and saprock in the study area range from (10-60) meters.

The distribution pattern of nickel laterite deposits in the study area spread in the eastern area has a relatively thicker thickness because it is indicated by a southwest - northeast oriented fault so that the western zone has a thinner layer of nickel laterite deposits around 10 meters.

ACKNOWLEDGMENT

Thanks to PT Antam Tbk for allowing researchers to research using company data. Thanks also to Geophysical Engineering of Universitas Pembangunan Nasional Veteran Yogyakarta for providing facilities for researchers to complete this research.

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