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The Contribution of Morphology to the Quantitative Potential of Nickel Laterite Deposits highly weathered ultramafic rocks in the Southeast Arm Region of Sulawesi Island, Indonesia

Kontribusi Morfologi terhadap Potensi Kuantitatif Endapan Nikel Laterit Batuan ultrabasa yang mengalami pelapukan tinggi di Wilayah Lengan Tenggara Pulau Sulawesi, Indonesia

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ABSTRACT
The research locations include Pomalaa in Kolaka Regency, Southeast Sulawesi, and Sorowako in East Luwu Regency, South Sulawesi. This study primarily aims to examine the comparative impact of morphology on the distribution of nickel ore enrichment zones and nickel ore thickness within laterite deposits in Southeast Sulawesi, specifically contrasting Pomalaa and Sorowako. The research was conducted in multiple phases: preparation (including planning for costs, timelines, and permits), data collection (which covers both field and laboratory analyses for material properties and geological information), data analysis (which involves laboratory tests utilizing XRF, petrographic studies, slope morphology evaluations, and profiles of lateritic nickel deposits), representation of morphology features in graphical format, and finally, compiling a scientific report based on the data analyses and interpretations. The relationship between characteristics of laterite profiles and morphology indicates that the steepness of slopes impacts water drainage and the lateralization process, with certain morphologies displaying superior thickness than others. Moreover, the thickness observed at some boreholes is affected not only by morphology but also by structural aspects, as indicated by favorable Rock Quality Designation (RQD) values. This study has mainly highlighted the effects of morphology and zone thickness on the nickel concentration found in laterite deposits. Therefore, it is suggested that further research should investigate additional factors, such as the structural properties of nickel laterite deposits.

Kata kunci: Bedrock, Morphology, Nickel Laterite, Rock Quality Designation (RQD)

ABSTRAK
Lokasi penelitian meliputi Pomalaa di Kabupaten Kolaka, Sulawesi Tenggara, dan Sorowako di Kabupaten Luwu Timur, Sulawesi Selatan. Penelitian ini bertujuan untuk mengkaji dampak perbandingan morfologi terhadap sebaran zona pengayaan bijih nikel dan ketebalan bijih nikel dalam endapan laterit di Sulawesi Tenggara, khususnya membandingkan Pomalaa dan Sorowako. Penelitian dilakukan dalam beberapa tahap: persiapan (termasuk perencanaan biaya, jadwal, dan izin), pengumpulan data (yang mencakup analisis lapangan dan laboratorium untuk sifat material dan informasi geologi), analisis data (yang melibatkan uji laboratorium menggunakan XRF, studi petrografi, evaluasi morfologi lereng, dan profil endapan nikel laterit), representasi fitur morfologi dalam format grafis, dan akhirnya, menyusun laporan ilmiah berdasarkan analisis dan interpretasi data. Hubungan antara karakteristik profil laterit dan morfologi menunjukkan bahwa kecuraman lereng memengaruhi drainase air dan proses lateralisasi, dengan morfologi tertentu menunjukkan ketebalan yang lebih unggul daripada yang lain. Selain itu, ketebalan yang diamati di beberapa lubang bor tidak hanya dipengaruhi oleh morfologi tetapi juga oleh aspek struktural, seperti yang ditunjukkan oleh nilai Rock Quality Designation (RQD) yang baik. Studi ini terutama menyoroti efek morfologi dan ketebalan zona pada konsentrasi nikel yang ditemukan dalam endapan laterit. Oleh karena itu, disarankan agar penelitian lebih lanjut menyelidiki faktor-faktor tambahan, seperti sifat struktural endapan laterit nikel.

Keywords*: Batuan dasar, Morfologi, Laterit Nikel, Rock Quality Designation (RQD)*

INTRODUCTION

The island of Sulawesi was formed through tectonic mechanisms composed of various continental and oceanic terranes (Hall, 2012; Hamilton, 1979; Surono and Hartono, 2013). The southeastern arm of Sulawesi is an amalgamation of continental terranes and the Cretaceous-aged Ophiolite Complex, followed by the deposition of the Sulawesi molasse sediments. These geological conditions and tectonic patterns played a role in the formation of potential laterite deposits in southeastern Sulawesi (Sorowako, Pomalaa, Bahodopi). Nickel laterite deposits are formed from further weathering of ultramafic rocks containing Ni-silicates, typically in sub-tropical to tropical regions near the. The study areas are located in Pomalaa, Kolaka Regency, Southeast Sulawesi, and Sorowako, East Luwu Regency, South Sulawesi. These areas are composed of ultramafic rocks that are part of the Ultramafic Complex. Ultramafic rocks primarily consist of olivine, pyroxene, hornblende, and mica. The abundant presence of olivine minerals in ultramafic rocks holds the potential for the formation of nickel laterite deposits. The type of rock in the bedrock greatly influences the formation of nickel laterites. Different lithologies will produce different mineral compositions, which in turn affect the geochemistry of nickel in a laterite deposit.

Nickel laterite deposits are defined as residual soils formed from the weathering of ultramafic rocks through leaching and supergene enrichment processes, controlled by morphology, geological structures, and groundwater fluctuations during their formation. The leaching of mobile elements in ultramafic rocks, such as silica and magnesium, results in the concentration of residual immobile elements, such as iron, nickel, and cobalt.

Morphological conditions significantly influence water circulation and other elements. In flat areas, water moves slowly, allowing it to penetrate deeper through rock fractures or pores. In steep areas, water flows on the surface, causing intensive erosion. Accumulation of deposits typically occurs in flat to moderately sloping areas. The thickness of nickel laterite deposits varies depending on the morphology in each area (Indra Kusuma, R.A., *et al*., 2019). Nickel laterite deposits can form in areas with moderate relief controlled by structures and fracture density. Areas with varying topographic slopes will result in nickel laterite deposits with different thicknesses (Thorne, R., *et al*., 2012). Accurate exploration targets to find nickel lat-

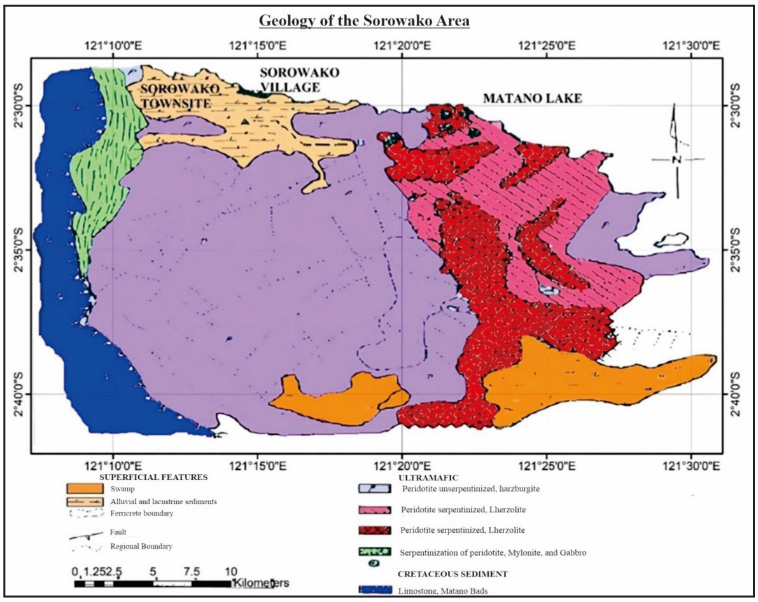

Figure 1. Regional Geological Map of Sorowako

erite deposits in Sulawesi are limited to areas in the Ultramafic Complex with a slope gradient ≤ 25%. The slope gradient of a morphology plays a controlling role in the weathering of rocks. Generally, the types of morphology that are potential for nickel laterite deposits include plateaus, terraces, hills, weakly undulating hills, and moderately undulating hills. In steep topographies (generally with slopes over 25%), weathering becomes less intensive as more water runs off rather than infiltrates (Anas, 2024).

The main focus of this study is to identify the comparative influence of morphology on the distribution of nickel ore enrichment zones and nickel ore thickness in laterite deposits in Southeast Sulawesi, specifically comparing the Pomalaa and Sorowako areas. By using a slope gradient analysis method correlated with chemical analysis data (with a cut-off grade of 1.1% Ni) and drill data on thickness, it is expected to identify the influence of morphology on ore enrichment zones and nickel ore thickness in the study areas.

The Southeastern Arm of Sulawesi exhibits complex and diverse geology due to its tectonic history. According to Van Bemmelen (1949), as cited by Surono, this region is divided into three zones: northern, central, and southern. The Kolaka sheet, which is located in the central to southern zone, lies within one of the most geologically dynamic areas. The study areas of Pomalaa and Sorowako are part of this zone.

The morphology of this region varies and consists of five main types: mountains, high hills, low hills, plains, and karst. However, the dominant geomorphology in the study area is low hills, particularly in the northern part of Kendari and the southern tip of the Southeastern Arm of Sulawesi. This area has undulating topography formed from Mesozoic and Tertiary-aged rocks, including ultramafic rocks that play a crucial role in the formation of nickel laterite deposits. (Panggabean, 2011)

The stratigraphy of the study area reflects the result of the collision between the Australian Plate and the Pacific Plate. In this region, two main terranes have formed: the Southeast Sulawesi Continental Terrane and the Matarombeo Terrane. The interaction between these plates resulted in subduction and collision processes that thrust ophiolite complexes from the Earth's mantle to the surface. These ophiolite complexes were then overlain by Sulawesi Molasse sediment deposits. It is these ophiolite complexes, containing ultramafic rocks, that serve as the primary source for the formation of nickel laterite deposits through supergene weathering processes.

This unique tectonic and geological setting not only influences the formation of rocks in the study area but also plays a significant role in the distribution and characterization of nickel laterite ore deposits. The dominant low hill morphology in the area allows for more intensive weathering processes, particularly on ultramafic rocks rich in minerals like olivine, pyroxene, and hornblende, all of which have the potential to produce economically valuable nickel laterite. (Ilham, 2021)

The geological structure of this region is characterized by left-lateral strike-slip faults with a primary orientation of southeast-northwest and northeast-southwest. Tectonic activity in this area includes the formation of the Verbeek and Moliowo mountain ranges, influenced by the Palu-Koro fault and the Palu-Mekongga tectonic zone. The tectonic history dates back to the Jurassic period when the Australian microplate moved northward, leading to subduction and collision with Southeast Sulawesi. This tectonic interaction resulted in folding and thrust faulting on Buton Island. The main fault in this area is the Kolono Fault, which cuts through almost all rock formations except for alluvial deposits. (Hasria, 2021).

RESEARCH METHODOLOGY

The stages of this research refer to the guidelines provided by the Ministry of Energy and Mineral Resources (2020), employing a qualitative field geology research method supported by laboratory analysis. The stages include: field

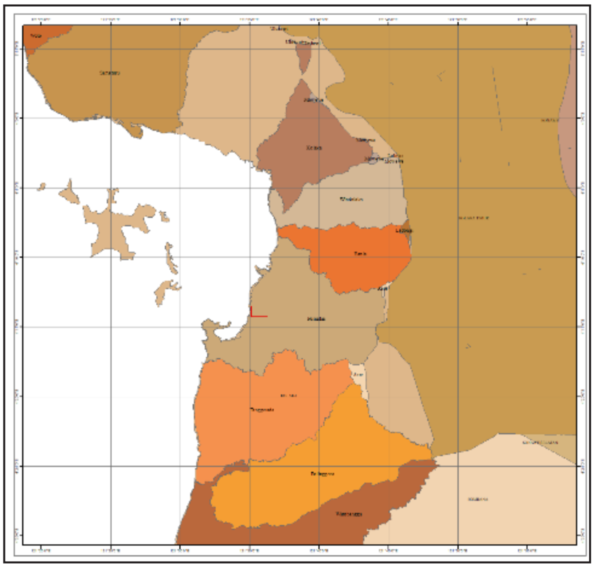

Figure 2. Location of the Research are.

data collection (lithology and geomorphology data), and laboratory data analysis (petrographic observations and chemical analysis) with a focus on geochemical analysis of rocks and minerals using XRF (X-ray fluorescence spectrometry) to identify the chemical composition of the rocks. The research follows several stages: preparation (planning for costs, time, and permits), data collection (both field and laboratory for material properties and geological data), data analysis (laboratory analysis using XRF, petrographic analysis, slope morphology analysis, and profile of lateritic nickel deposits), morphology characteristics represented in graphical form, followed by the drafting of a scientific report based on the data analysis and interpretation.

RESULT AND DISCUSSION

In the Pomalaa area, there are ultramafic rocks identified through megascopic observations of their physical properties and mineral composition in the morphology of steep and undulating hills. These peridotite rocks, with fresh blackish-green color and weathered reddish-brown, exhibit a holocrystalline structure with coarse grains, euhedral to anhedral mineral shapes, equigranular grain distribution, and a mineral composition that includes pyroxene, olivine, plagioclase, as well as alteration minerals such as serpentinite and garnierite, reinforcing the identification as peridotite according to the criteria defined by Fenton in 1940.

The microscopic characteristics of peridotite

Figure 3. Macroscopic features of peridotite outcrops at ST 01, with mineral composition including pyroxene, olivine, plagioclase, and alteration minerals such as serpentine and garnierite, photographed in the direction of N 180° E.

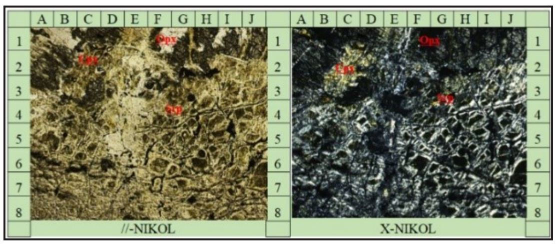

Figure 4. Petrographic features of serpentinite rocks at ST 01, with mineral composition including orthopyroxene (Opx), clinopyroxene (Cpx), and serpentine (Srp).

rocks in the Pomalaa area show colors ranging from colorless to brownish-white in parallel nicols and white to yellow in crossed nicols. The rocks exhibit a fully crystalline texture, coarse granularity, and variable mineral shapes with sizes ranging from 0.2 to 2 mm. The main mineral composition consists of serpentine (85%), clinopyroxene (10%), and orthopyroxene (5%), with serpentine forming veinlets that penetrate the pyroxene, indicating a complete serpentinization process. Therefore, these rocks are classified as Serpentinite according to Travis in 1955.

However, some other locations around the Pomala area have variations in bedrock rocks in the laterite profile. The appearance of petrographic sections of P-01 shows colorless to gray absorption colors, varying interference colors (according to the color of the minerals), holocrystalline crystallinity rock texture, phaneritic granularity, anhedral - subhedral mineral forms, equigranular fabric. The composition of the minerals that make up this rock is olivine (45%), clinopyroxene (23%), orthopyroxene (22%), and opaque (10%). The name of the rock is Lherzolite.

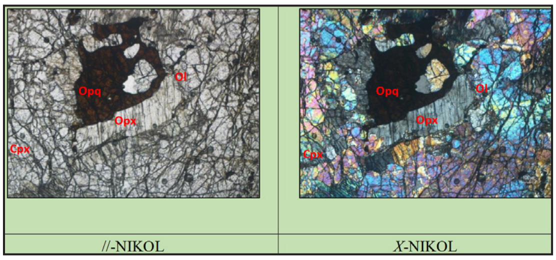

Figure 5. Microscopic features in section P-01 are composed of olivine (45%), clinopyroxene (23%), orthopyroxene (22%), and opaque minerals (10%).

The appearance of the petrographic section of P-02 shows colorless to gray absorption color, interference color varies (according to the color of the mineral), holocrystalline crystallinity rock texture, phaneritic granularity, subhedral-anhedral mineral form, inequigranular fabric. The composition of the minerals that make up this rock are olivine (55%), orthopyroxene (35%), Clinopyroxene (5%) and opaque (5%). The name of the rock is Hazburgite.

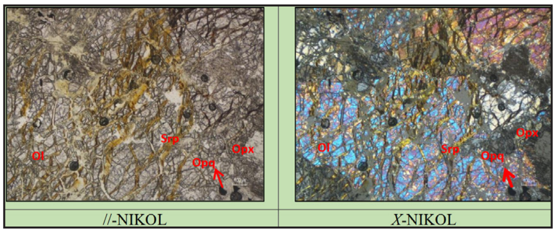

Figure 6. Microscopic features in section P-02 are composed of olivine (55%), orthopyroxene (35%), clinopyroxene (5%), and opaque minerals (5%).

In the petrographic section of the rock from drill hole C359031, section number D-HD/FM/C359031, the sample is identified as ultramafic igneous rock with a phaneritic texture. The interference colors observed are grayish-white, reddish-yellow, brown, and black, while the absorption colors are colorless, brown, and black. The mineral sizes range from 0.25 mm to 2.5 mm, and the mineral shapes are.

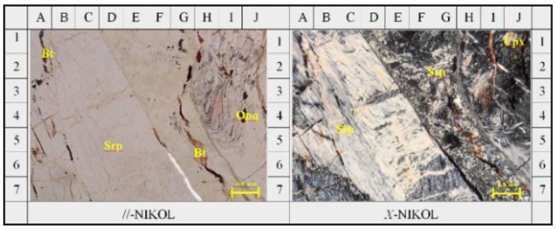

Figure 7. Microscopic features in section D-HD/FM/C359031 are composed of serpentine (87%), clinopyroxene (8%), biotite (4%), and opaque minerals (1%).

The minerals encountered are euhedral to anhedral, with low to high relief, exhibiting no pleochroism or fractures. Certain minerals display cleavage, and their light transmission ranges from transparent to opaque. The mineral composition in this section includes serpentine (87%), clinopyroxene (8%), biotite (4%), and opaque minerals (1%). By correlating the results from this section description with Travis's classification of igneous rocks (1955), this rock is identified as Serpentinite (Figure 7).

The research areas of Pomalaa and Sorowako feature a laterite layer at the surface with a thickness ranging from 5 to 20 meters. However, subsurface data from 41 drillings indicate variations due to the laterization process, which is influenced by morphology and topography. The cross-section profile of the laterite based on subsurface geological data will be discussed further.

Figure 8. Outcrop features of the laterite profile in the Pomalaa area.

At the surface, there is a limonite zone with reddish-brown to yellowish colors, rich in iron minerals, and a saprolite zone characterized by weathered peridotite rocks with a greenish color due to the laterization process. The saprolite is dominated by serpentine and garnierite minerals, with goethite present in the transition zone. The parent rock is peridotite, which is rich in mafic minerals and serpentine.

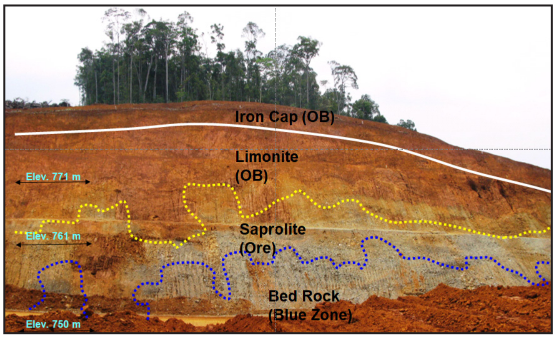

Figure 9. Laterite profile in the Sorowako area.

There are boulders in the saprolite zone at a depth of 1 - 1.5m, the presence of boulders greatly affects the lack of percentage volume of Ni content in the saprolite zone and the saprolite zone is shown at 0-2 meters marked by enrichment of Ni elements (0.57%) and elements such as Fe (11.31%), SiO2 (43.88%), MgO (21.64%) are still found. This is due to the semi-mobile nature of the elements and will decrease with increasing depth or approaching the bedrock layer. The bedrock zone is characterized by a significant decrease in the levels of each element and leaves SiO2 and MgO which are still high. These two elements are commonly found and their levels are getting higher in bedrock. This is due to the highly mobile nature of the elements which causes the elements to move following the bedrock. The bedrock that makes up the drill point is serpentinite.

Landform classification was conducted using three approaches: morphography, morphometry, and morphogenesis. The study area features convex peaks with elevations ranging from 25 to 280 meters above sea level, classifying it as a hilly area according to Zuidam (1985) in Hasria (2021). The primary geomorphological process is weathering, with laterization soil thickness reaching approximately 20 meters, indicating reddish-brown residual soil with a limonite zone. Further analysis confirms the area as a denudational hill. Morphometric analysis of slope gradients and topographic shapes revealed close contours and slope gradients of 15°-30°. The morphology observed based on elevation and slope gradient at the study site, including borehole locations, was analyzed using slope classification and the relationship between absolute elevation and morphography (Zuidam (1985) in Hasria (2021)).

Elevation and slope gradient the Pomalaa study area are slope gradient in 80°–160° and elevation on 220–260 m (Steep Hills); slope gradient in 80°–160° and elevation on 100–190 m (Undulating Hills); slope gradient in 80°–160° and elevation on 50–90 m (Gently Sloping Undulating Hills); slope gradient in 40°–80° and elevation on 210–260 m (Gentle Hills); and slope gradient in 40°–80° and elevation on 20–40 m (Gently Sloping Undulating Plains)

Furthermore, slope gradient Sorowako study area are Gentle Slope (7 – 15%), Moderately Steep (15 – 30%), Steep (30 – 70%), and Very Steep (70 – 140%).

This study focuses on understanding subsurface geological conditions through drilling processes to obtain critical data for geological interpretation. The goal is to identify the profile of laterite layers (limonite and saprolite) and bedrock. This research utilizes topographic data to be compared with the laterite layers from drilling results and creates 9 cross-sectional lines from 42 boreholes to show the variation in laterite characteristics based on their thickness and the morphology of the study area.

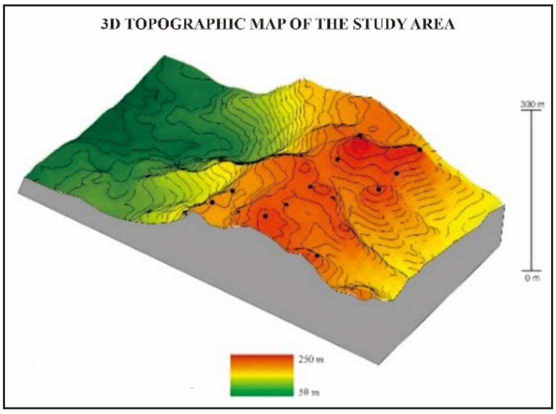

Figure 10. Three-dimensional topographic map of the research area with cross section lines.

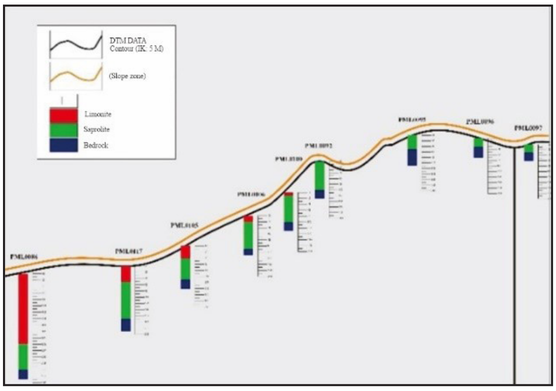

Figure 11. Cross-section of borehole data A-B.

The cross-section in zone A runs from borehole PML0086 to PML0097, connecting five types of morphologies with varying slopes and elevations. The gently undulating plain at PML0086 has a slope of 40-80 and an elevation of 20-40 meters. The gently sloping hills at PML0117 and PML0105, as well as the rolling hills at PML0106, have a slope of 80-160 and increasing elevations from 50 to 190 meters. The gentle hills at PML0100 and PML0095, as well as the steep hills at PML0092, PML0096, and PML0097, exhibit similar variations in elevation and slope. Data on Ni, MgO, and Fe are presented in three categories: Maximum, Average, and Minimum.

The table shows differences in the thickness of laterite deposits (limonite and saprolite) between boreholes in different slope zones of area A. Borehole PML0086, located on a gently undulating plain with a slope gradient of 40-80 and an elevation of 20-40 meters, has a laterite deposit thickness of 33 meters, thicker than the other boreholes in this section. Three laterization zones were identified here, as the low slope allows for maximum water penetration, optimizing the laterization process. The element distribution at this point is considered normal, with high Fe levels in the limonite zone, high Ni levels in the saprolite zone, and high MgO levels in the bedrock.

Other boreholes, such as PML00117 and PML0105, are located on gently sloping hills with a slope gradient of 80-160 and an elevation of 50-90 meters. The laterite thickness here is 20 meters and 15 meters, respectively, with three well-defined laterization zones, as the moderate slope allows for good water penetration.

However, at borehole PML0106, located in rolling hills with a slope gradient of 80-160 and an elevation of 100-190 meters, although the laterite deposit thickness is 10 meters, no limonite zone was found, likely due to erosion or runoff that hinders optimal water penetration because of the steep slope.

A similar situation occurs at boreholes PML0100 and PML0095, located in gentle hills with a slope gradient of 40-80 and an elevation of 210-260 meters. Although the laterite thickness is 13 meters and 11 meters, respectively, no limonite zone was found, likely due to erosion or runoff affecting water penetration due to the steep slope.

Table 1. Distribution of element accumulation and thickness of borehole data A-B

SLOPE ZONE A									
PML0086									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	0,586	0,891	0,709	1,005	1,568	1,2659	0,97	1,36	1,20667
Fe (%)	43,26	51	46,3447	49,763	53,417	52,0163	16,04	22,,62	20,2467
MgO (%)	1,24	2,07	1,64333	1,01	2,08	1,427	16,01	16,16	12,76
Depth		22			8			3	
Topography				Gently Undulating					
PML0117									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	0,6	0,9	0,75	0,26	1,76	0,9	0,23	0,38	0,29
Fe (%)	42,26	46	43,88	3,47	9,11	5,02	5,54	5,98	5,79
MgO (%)	1,1	2,1	1,58	16,88	34,71	26,4	33,69	34,53	33,98
Depth		5			12			4	
Topography				Sloping Undulating Hills					
PML0105									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	1,1	1,2	1,15	0,93	2,18	1,72857	0,26	0,31	0,282
Fe (%)	19	27	22,75	7,57	17	12,0757	6,31	7,25	6,744
MgO (%)	9,5	14,5	12	9,82	27,5	19,67	30,42	33,44	31,798
Depth		4			7			3	
Topography				Sloping Undulating Hills					
PML0106									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	1,129	1,209	1,169	0,29	1,09	0,64	0,25	0,36	0,29333
Fe (%)	19,597	26	23,2155	6,14	15,21	Oct-86	5,71	7,66	6,61333
MgO (%)	9,86	14,72	12,29	16,4	31,86	24,0414	29,43	33,03	31,36
Depth		2			10			2	
Topography				Rolling Hills					
PML0100									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	1,4	1,4	1,4	0,49	1,91	1,23333	0,31	0,46	0,39333
Fe (%)	23,36	23	23,36	6,73	20,02	11,52	5,7	6,43	6,12333
MgO (%)	7,94	7,94	7,94	11,82	36,89	22,6378	33,6	37,22	35,04
Depth		1			9			3	
Topography				Gently Hills					
PML0092									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)				0,25	1,66	0,91231	0,23	0,3	0,26
Fe (%)				5,38	11,76	8,60077	5,61	6,26	5,85
MgO (%)				18,49	38,2	26,4008	35,71	38,95	37,6733
Depth					10			3	
Topography				Steep Hills					
PML0095									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)				0,98	1,61	1,30667	0,22	0,42	0,28667
Fe (%)				9,39	11,82	10,8883	5,17	6,28	5,81167
MgO (%)				17,03	22,66	19	32,18	38,31	35,5233
Depth					5			6	
Topography				Gently Hills					
PML0096									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)				0,91	1,03	0,97167	0,214	0,289	0,26525
Fe (%)				8,673	16,436	12,208	5,684	5,943	5,782
MgO (%)				13,84	27,01	20,61	39,35	40,34	39,8925
Depth					3			4	
Topography				Steep Hills					
PML0096									
	LIM			SAP			BRK		
Element	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)				0,26	0,48	0,365	0,22	0,23	0,22333
Fe (%)				6,44	10,58	8,52	6,24	6,28	6,3
MgO (%)				24,18	37,63	29,7625	38,35	39,09	38,7933
Depth					3			3	
Topography				Steep Hills					

Meanwhile, boreholes such as PML0092, PML0096, and PML0097, located in steep hills with a slope gradient of 80-160 and an elevation of 220-260 meters, have laterite thicknesses of 13 meters, 7 meters, and 6 meters, respectively, with no limonite zone identified due to the slope conditions, which do not support optimal water penetration.

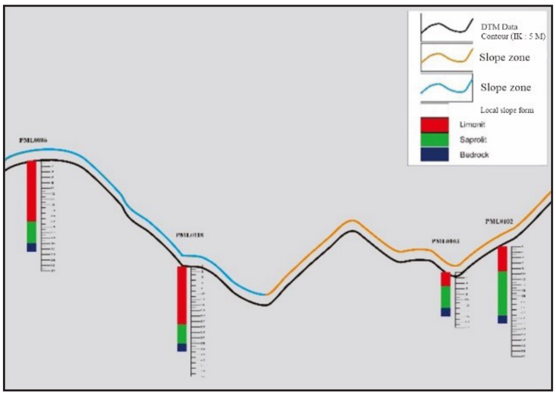

Figure 12. Borehole data section O-P.

This cross-section spans two slope zones, namely slope zone A and B. Slope zone A intersects boreholes PML0103 and PML0102, while slope zone B intersects boreholes PML0086 and PML0118. The cross-section passes through one landform, which is a gently undulating plain (with a slope gradient of 40-80 and an elevation of 0-40 meters) at boreholes PML0086, PML0118, PML0103, and PML0102. The values of Ni, MgO, and Fe concentrations are categorized into three ranges: Maximum, Mean (Average), and Minimum, as shown in the following table (Table 2).

Boreholes PML0086 and PML0118, located in slope zone B, as well as PML0103 and PML0102, situated in slope zone A, exhibit the morphology of a gently undulating plain, with laterite deposit thicknesses of 33 m, 31 m, 14 m, and 28 m, respectively. The discovery of these three laterization zones is attributed to the sloping terrain indicated in the borehole data, which allows for optimal water infiltration, thereby enhancing the laterization process. The distribution of elements at these boreholes is relatively normal, with the saprolite zone displaying high Ni content and the underlying rock rich in MgO.

Topography is not the only major factor in the formation of laterite nickel; structural factors also play a crucial role. In this context, the calculation of Rock Quality Designation (RQD) at the ID Hole of the cross-section becomes relevant. There are four boreholes in this cross-section, with RQD values ranging from 65.2% to 77.5%. The rocks in this cross-section exhibit numerous fractures, which serve as pathways for water that transports Ni elements. This results in a greater thickness of the saprolite zone in this type, with a tendency for higher Ni content. In Hole ID PML0102, an analysis of fracture values and Rock Quality Designation (RQD) was conducted at a depth of 18 to 28 meters,

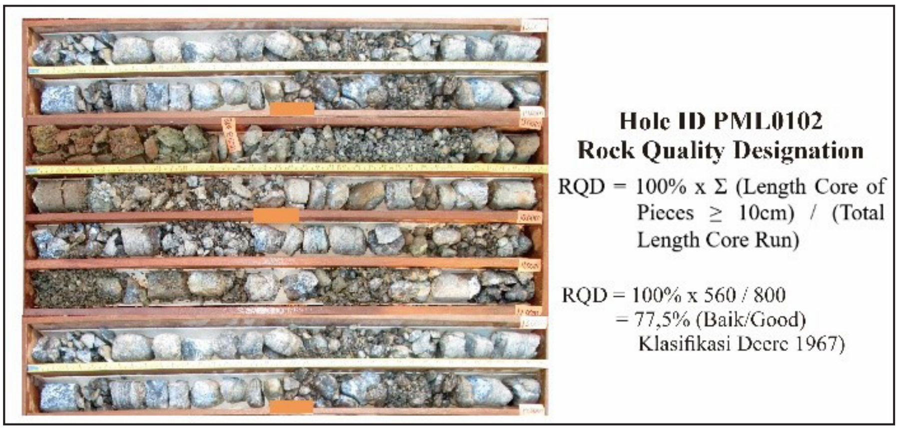

Figure 13. Calculation of RQD for Borehole ID PML0102

Table 2. Distribution of element accumulation and thickness of borehole data section O-P

				SLOPE ZONE A					
				PML 0103					
		LIM			SAP			BRK	
Unsur	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	1,32	1,38	1,35	0,37	2,65	1,58818	0,28	0,45	0,34333
Fe (%)	26,24	43,32	34,78	6,52	13,78	9,91909	6,03	6,19	6,11667
MgO (%)	1,12	7,39	4,225	20,35	32,02	25,1355	31,45	35,3	33,8933
Depth		5			9			3	
Topography					Gently Undulating Plain				
				PML 0102					
		LIM			**SAP**			**BRK**	
Unsur	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	0,99	1,43	1,25125	0,56	2,56	1,61579	0,25	0,34	0,28
Fe (%)	41,62	48,72	46,2925	6,54	6,54	19,1716	5,54	6,17	5,79667
MgO (%)	0,4	0,85	0,56125	1,56	1,56	15,7353	33,19	35,4	34,3833
Depth		9			16			3	
Topography					Gently Undulating Plain				
				SLOPE ZONE B					
				PML 0086					
	LIM			**SAP**			**BRK**		
Unsur	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	0,586	0,891	0,709	1,005	1,568	1,2659	0,97	1,36	1,20667
Fe (%)	43,26	51,051	46,763	49,763	53,417	52,0163	16,04	22,62	20,2467
MgO (%)	1,24	2,07	1,01	1,01	2,08	1,427	10,62	16,16	12,67
Depth		22			8			3	
Topography					Gently Undulating Plain				
				PML 0118					
		LIM			**SAP**			**BRK**	
Unsur	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ni (%)	0,51	1,5	0,67	0,29	1,68	0,87	0,28	0,54	0,41
Fe (%)	22,61	42,24	39,67	6,92	10,28	8,35	6,34	10,98	8,84
MgO (%)	1	10,57	2,16	23,11	32,42	28,03	27,49	34,49	31,02
Depth		21			7			3	
Topography					Gently Undulating Plain				

which corresponds to the bedrock and saprolite zones containing boulders. The total length of drilling in this zone is interpreted to be 8 meters (total length core run), with 18 observed natural fractures. The total length of boulders (>10 cm) resulting from these fractures is 5.6 meters. Therefore, the RQD percentage for this hole is calculated as follows: (RQD = ((Total length of boulders (>10 cm)(Total length core run)) x 100% = (5.6/8)100%)) = 70\%). Based on the classification by Deere (1967), this level of fracturing is categorized as "good," indicating favorable conditions for water supply during the laterization process. The correlation between the concentrations of elements in the laterite deposits and the slope gradient in the study area can be seen in the graph below.

To determine the distribution of thickness, Ni and Fe content in laterite deposits in relation to slope gradients, an overlay of maps was performed. The results of this overlay are presented in a map and table. The table outlines the distribution data for each class of the

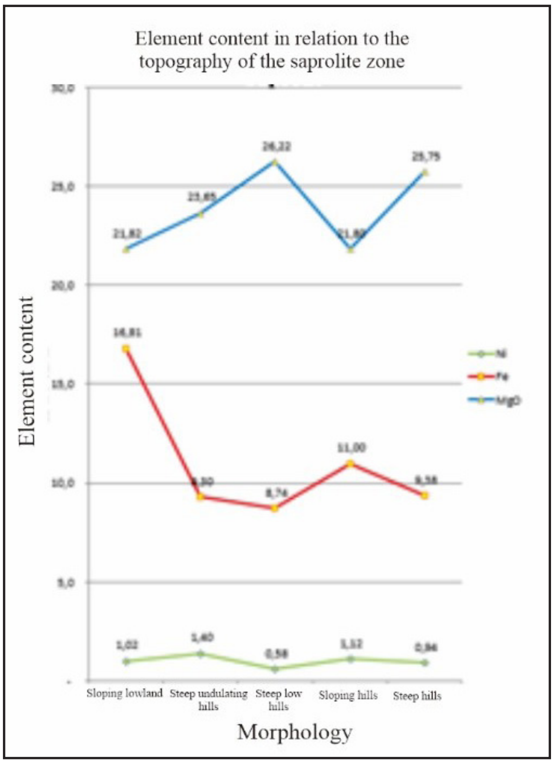

Figure 14. Correlation line diagram of element concentration with element concentration in the saprolite zone.

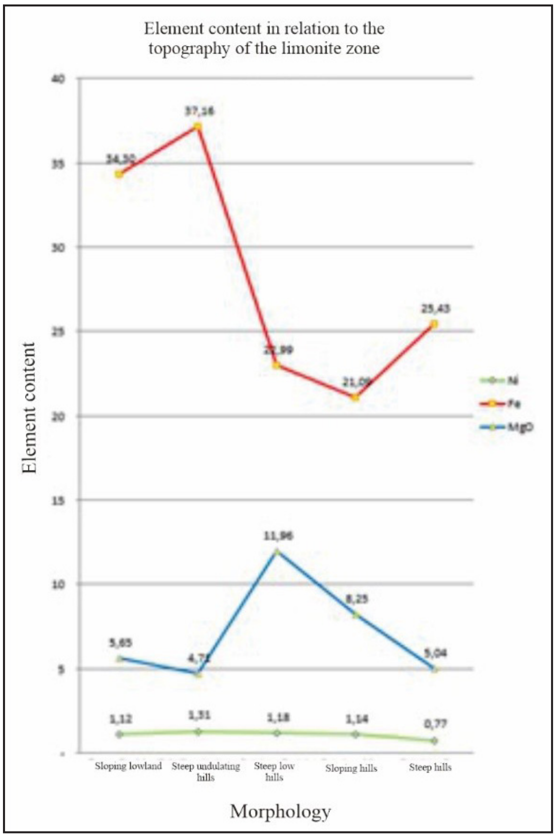

Figure 15. Correlation line diagram of element concentration with element concentration in the limonite zone.

examined aspects, including the slope gradient from each borehole and the Ni and Fe content, as well as the thickness encountered in this area. The boreholes encountered along the E – E' cross-section are C359022, located on a moderately sloping terrain, C196853, located on a steep slope, and C173209, situated on a moderately steep slope.

Figure 16 shows the profile thickness of the laterite deposit, highlighting the presence of limonite and saprolite zones based on encountered drilling data. According to the graph, the average thickness of the limonite zone is 4 meters, while the saprolite zone averages 14 meters.

Figure 17 illustrates the mobility of Ni elements at three borehole locations, indicating a trend of increased Ni concentration from the lower part of the limonite zone to the middle part of the saprolite zone. A subsequent decrease in Ni concentration occurs from the lower saprolite zone to the bedrock. This suggests that the mobility of Ni is semi-mobile, with Ni elements tending to react when groundwater conditions are acidic. When the pH of the groundwater rises to neutral, these elements become less soluble in the lower lateritization zone, causing Ni to accumulate in the saprolite zone.

The boreholes encountered in section F-F' are C359023, located on a moderately steep

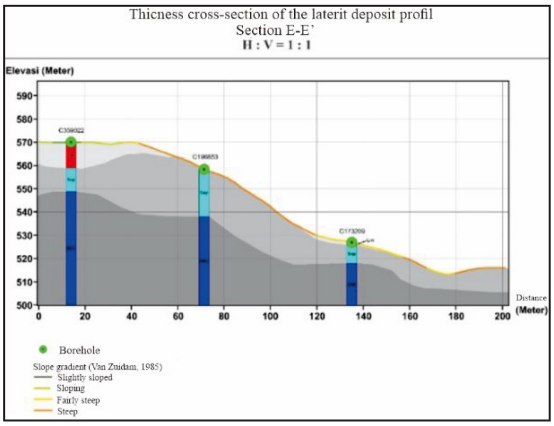

Figure 18. Borehole data section F-F'.

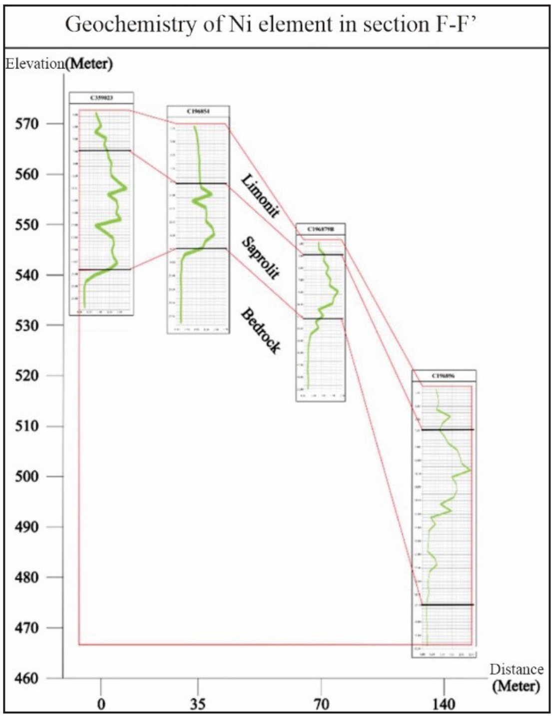

Figure 19. Ni element mobility section F-F'.

slope; C196854, located on a gently sloping area; C196879B, located on a steep slope; and

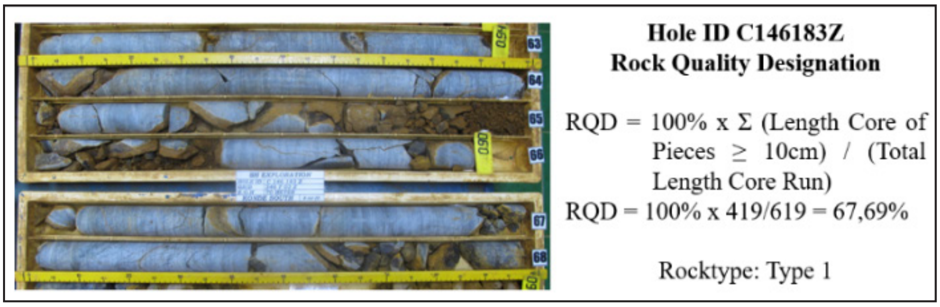

Figure 20. RQD calculation for hole ID C146183Z.

C196896, located on a moderately steep slope.
Figure 18 shows the thickness profile of laterite deposits, highlighting the presence of limonite and saprolite zones based on encountered drilling data. Statistically, the average thickness of the limonite zone is 6.75 meters, while the saprolite zone has an average thickness of 12.29 meters.

Figure 19 illustrates the mobility of Ni elements across four boreholes, showing a trend where Ni concentrations increase from the lower limonite zone to the middle saprolite zone, followed by a decrease in Ni levels from the lower saprolite zone down to the bedrock.

This indicates that Ni is semi-mobile, with a tendency to react when groundwater conditions are acidic. When the groundwater pH rises to neutral, Ni becomes less soluble, preventing further downward migration into the lower laterization zones. This process leads to the accumulation of Ni in the saprolite zone.

Topography is not the only major factor influencing nickel laterite formation; structural factors also play a significant role. In this context, the RQD (Rock Quality Designation) calculations at hole IDs in the cross-section are relevant. There are three boreholes in this section, with RQD percentages ranging from 65.2% to 77.5%. The rocks in this section have numerous fractures, which act as pathways for water carrying Ni elements. As a result, the saprolite zone in this area is thicker, with a higher Ni content.

RQD was conducted at depths of 26-37 meters, covering the boulder saprolite to bedrock zones. The total core run length in this zone was 4.19 meters. A total of 39 natural fractures were observed, and the cumulative length of boulders (>10 cm) resulting from these fractures was 6.19 meters. The RQD percentage, calculated as:{RQD} = ({Total length of boulders (>10 cm)}}{Total core run length) }}100\%). For this borehole, the RQD is 67.69%.

CONCLUSION

This study presents data on the morphology and laterite profile characteristics in the Pomalaa and Sorowako regions. In Pomalaa, five morphologies were observed: Steep Hills, Rolling Hills, Gently Sloping Hills, Flat Hills, and Undulating Plains. In Sorowako, four slopes were identified: Gentle (7–15%), Moderately Steep (15–30%), Steep (30–70%), and Very Steep (70–140%). The characteristics of laterite deposits in Pomalaa for each morphology are determined by the thickness and composition of elements such as Ni, Fe, and MgO. Overall, the thickness and elemental composition vary across different laterite zones in each morphology. The correlation between laterite profile characteristics and morphology shows that slope steepness affects water drainage and the laterization process, with certain morphologies displaying better thickness than others. Additionally, the thickness at some boreholes is not solely influenced by morphology but also by structural factors, as evidenced by favorable RQD values. Furthermore, the correlation of Ni content with the laterite profile shows variation, with some morphologies exhibiting good Ni content, while others show less favorable results based on the company's COG values.

In Sorowako, laterite deposits play a crucial role in controlling the fluctuation of maximum values of thickness and Ni content on slopes with a 7-15% grade (Gentle). The factors causing distribution patterns in the tested aspects, despite having similar morphologies, are the uneven weathering of the laterite deposits and the methods used in determining the distribution. The correlation between the company's COG and SOP values and the aspects controlled by morphology (laterite deposit thickness and Ni content) in determining ore zones tends to be directly proportional in the study area. If both aspects have high values, the ore zone is also likely to have greater thickness and higher content. The role of morphology in laterite nickel exploration serves as an initial interpretation of location potential, helping to reduce production costs in exploration by mapping areas with high Ni potential based on morphological conditions.

RECOMMENDATIONS

The author suggests further research on the factors influencing the formation of laterite deposits to enhance understanding of the potential and management of nickel laterite resources in Indonesia.

This is important for gaining a more in-depth understanding and exercising caution when interpreting the distribution of nickel laterite deposits, as many factors affect the content of these deposits. This study has primarily identified the influence of morphology and zone thickness on the nickel content in laterite deposits. Therefore, additional research on other factors, such as the structural characteristics of nickel laterite deposits, is recommended.

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