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RESEARCH ARTICLE

Characteristics of Nickel–Cobalt (Ni–Co) Enrichment in Lateritic Nickel Deposits of Pakal Island, Maba District, East Halmahera Regency, North Maluku Province

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Abstract

The increasing global demand for cobalt, projected to reach 390,000 tons by 2030, has drawn growing attention to the potential of laterite deposits as strategic mineral resources, particularly in ultramafic rock regions such as eastern Indonesia. This study was conducted on Pakal Island, Maba District, East Halmahera, North Maluku. It aims to examine the geological conditions, geochemical characteristics of nickel laterite deposits, and the enrichment of cobalt (Co) in the study area. The methods employed include geological field mapping, rock sampling, and laboratory analyses involving petrography, XRD, XRF, and SEM-EDX. The results show that the Dunit and Harzburgit units contain olivine, orthopyroxene, and serpentine minerals. The limonite zone contains hematite, goethite, and lithiophorite, while the saprolite zone contains garnierite and enstatite. Co enrichment is predominantly found in the limonite layer (0.12–0.15%) and is influenced by lithology, degree of serpentinization, topography, geological structures, and the tropical climate, which accelerates chemical weathering. The vertical distribution of Co shows an inverse correlation with Ni. These findings contribute to the understanding of the formation processes and characteristics of nickel cobalt laterite deposits in eastern Indonesia and provide a scientific basis for future exploration of cobalt-based strategic mineral resources

Keywords: Cobalt (Co), lateritic nickel, Pakal Island, geochemistry, serpentinization, limonite, mineral exploration.

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1. Introduction

The significant increase in global cobalt demand, with a growth rate of 7–13% per year, opens up significant opportunities for cobalt-producing countries. This demand is projected to reach 390,000 tons by 2030, following the global trend towards more environmentally friendly industries (Hassani & Dahani, 2024). With this increase, cobalt resources are very promising for processing as future raw materials. As a country with significant natural resource potential, Indonesia has a strategic opportunity to contribute to meeting global cobalt needs. Indonesia holds cobalt resources in nickel-cobalt laterite deposits that have the potential to become one of the world's cobalt suppliers. Nickel-cobalt laterite deposits are products of the weathering of ultramafic rocks from the ophiolite complex spread across eastern Indonesia.

Fig 1. Graph of world Cobalt needs

Cobalt plays a vital role in various chemical industry applications, particularly as a catalyst. Approximately nine percent of total cobalt use, or approximately 2,700 tons per year, is used in the catalytic industry, particularly in the petrochemical sector. In this sector, cobalt oxide is used in the desulfurization of crude oil to produce cleaner, more environmentally friendly fuels. Furthermore, cobalt-based catalysts are also used in gas-to-liquid technology, the process of converting natural gas into synthetic diesel fuel, which is expected to grow rapidly as demand for clean energy increases. In the plastics sector, cobalt acetate compounds combined with manganese and sodium bromide are used in the production of certain plastics, indicating that cobalt's use is becoming increasingly widespread and diversified in the modern chemical industry.

Global demand for cobalt is expected to continue to increase to reach 390 thousand tons by 2030, which has encouraged various countries, including Indonesia, to study the potential of domestic cobalt resources. This research was conducted on Pakal Island, Maba District, East Halmahera Regency, North Maluku Province, which is geologically located in an area composed of ultramafic rocks resulting from the ophiolite complex. Based on the Regional Geological Map of the Malili and Bungku sheets, it is known that this area contains ultramafic rocks such as harzburgite and dunite which are included in the Ultramafic Complex (Ku) (Simandjuntak et al., 1991; Rusman et al., 1993). Ultramafic rocks that undergo a laterization process produce economically valuable metal ore deposits such as cobalt (Co), chromite (Cr), nickel (Ni), and magnetite (Natua et al., 2024). Therefore, by understanding the characteristics of ultramafic rocks and the mechanism of cobalt element enrichment, this research is expected to contribute to the development of cobalt mineral exploration strategies in the future, especially in laterite deposits in eastern Indonesia.

2. Research Methodology

This research was conducted in several stages, beginning with a preliminary study involving proposal preparation, administrative processing, and literature review to gain an initial understanding of the regional and local geological conditions on Pakal Island, Maba District, East Halmahera Regency. The next stage involved collecting field data through geological mapping and outcrop observations to identify lithology and geological structures, and collecting rock samples from the limonite, saprolite, and bedrock zones.

The samples were then analyzed in the laboratory using various methods to obtain mineralogical, geochemical, and microscopic textural data. Petrographic analysis was performed on thin sections of the rocks using a polarizing microscope to identify the mineral constituents and textures of the rocks, and to determine the rock classification based on Le Maitre (2002) for ultramafic igneous rocks and O'Dunn & Sill (1986) for metamorphic rocks. X-ray diffraction (XRD) analysis was used to identify crystalline minerals and mineral alteration zones, which are important in understanding the laterite formation process.

Fig 2. XRF Analysis

To determine the content of major and minor elements, especially nickel (Ni) and cobalt (Co), geochemical analysis using the X-Ray Fluorescence (XRF) method was used, the results of which were used to determine rock type, tectonic environment, and metal enrichment patterns.

Fig 3. SEM-EDX Analysis

In addition, SEM-EDX (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy) analysis was conducted to obtain a microscopic topographic image of the rock surface and analyze the distribution and content of cobalt elements in the carrier minerals. All the analysis results were then integrated to produce a geological interpretation of the study area, the vertical distribution of metal elements, and the characteristics of cobalt enrichment in the laterite nickel deposits of Pakal Island, which are presented in the form of maps, diagrams, and scientific narratives.

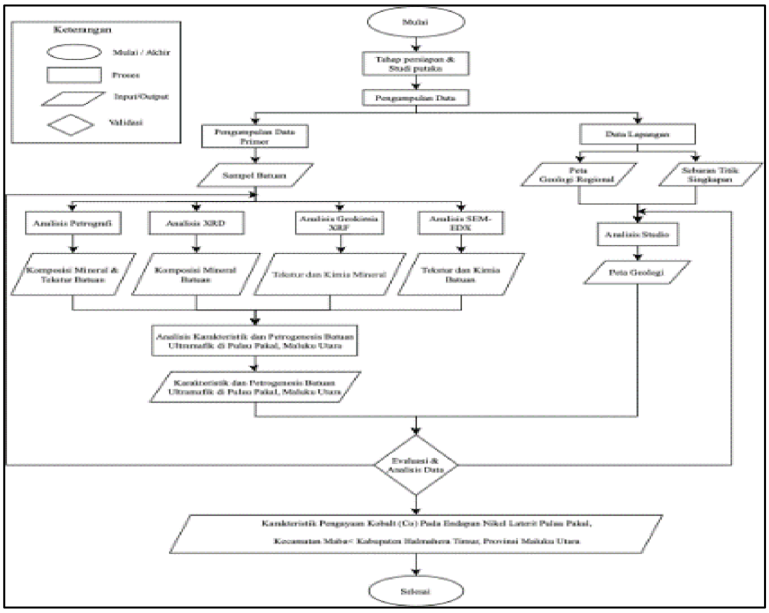

Fig 4. Research Flow Chart

3. Results and Discussion

3.1 Stratigraphy of the Research Area and Profile of Nickel Laterite Deposits

Stratigraphically (Fig 5), the study area is composed of a

Complex sequence of rocks, starting from the Dunite Rock Unit and the Harzburgite Rock Unit present in the Ultrabasic Rock Complex. These rock units form the base rock (protolith) of the laterite nickel deposits that are the focus of the study. Based on regional comparability according to (Apandi and Sudana, 1980) the rock units are of Cretaceous age.

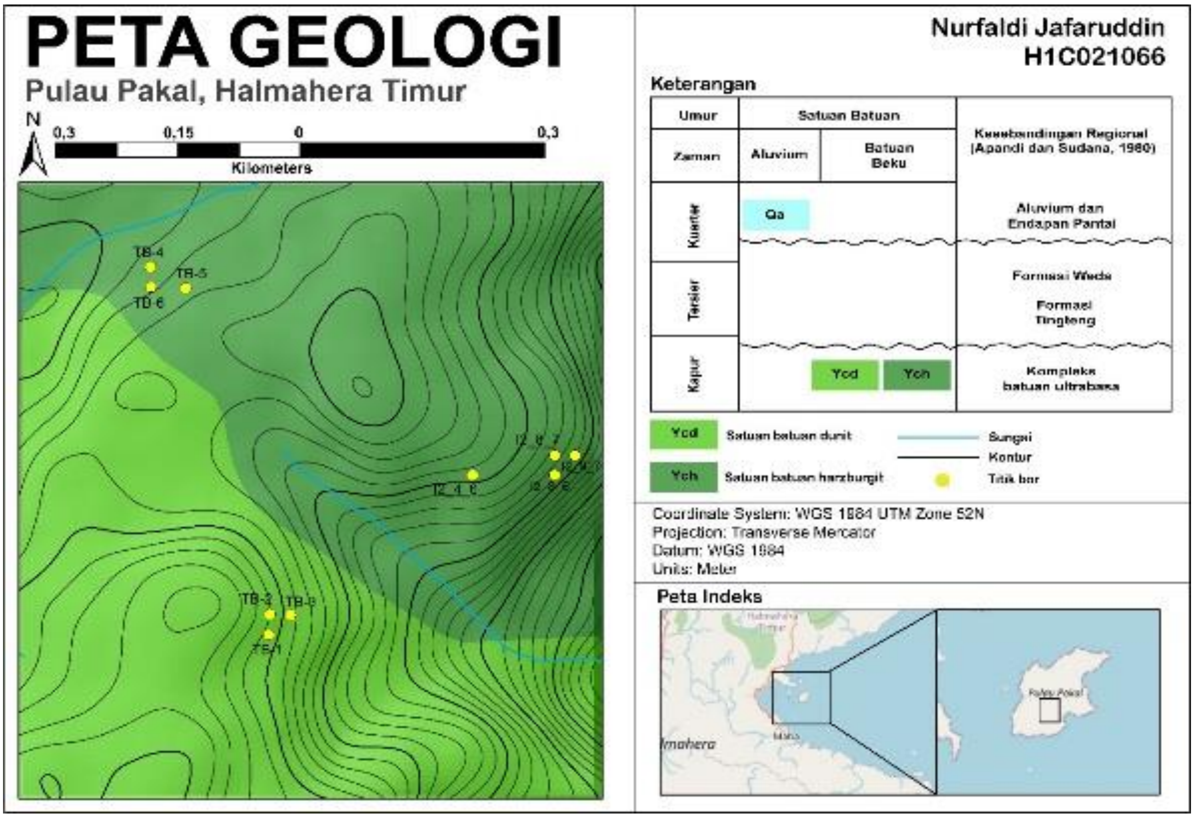

Fig 5. Geological Map of Research Area

Based on petrographic analysis (Figure IV.3) shows a dominant green-brownish color in cross nicols and a dominant gray color in parallel nicols. Interference colors from gray to high order in cross nicols. Massive structure with a typical mesh and interpenetrating texture in serpentine minerals (lizardite and antigorite). Primary minerals (olivine and orthopyroxene) have been partially replaced by secondary minerals with irregular replacement boundaries. Some parts show vein textures with elongated serpentine minerals. Chromite is present as an opaque mineral with sharp boundaries. Mineral forms vary from anhedral to euhedral with non-uniform sizes (inequigranular). Overall, this rock is a serpentinized peridotite with pseudomorphic and relict textures that still retain traces of the original minerals. It has a mineral composition of olivine (90%), orthopyroxene (5%), chromite (1%), lizardite (3%), antigorite (1%).

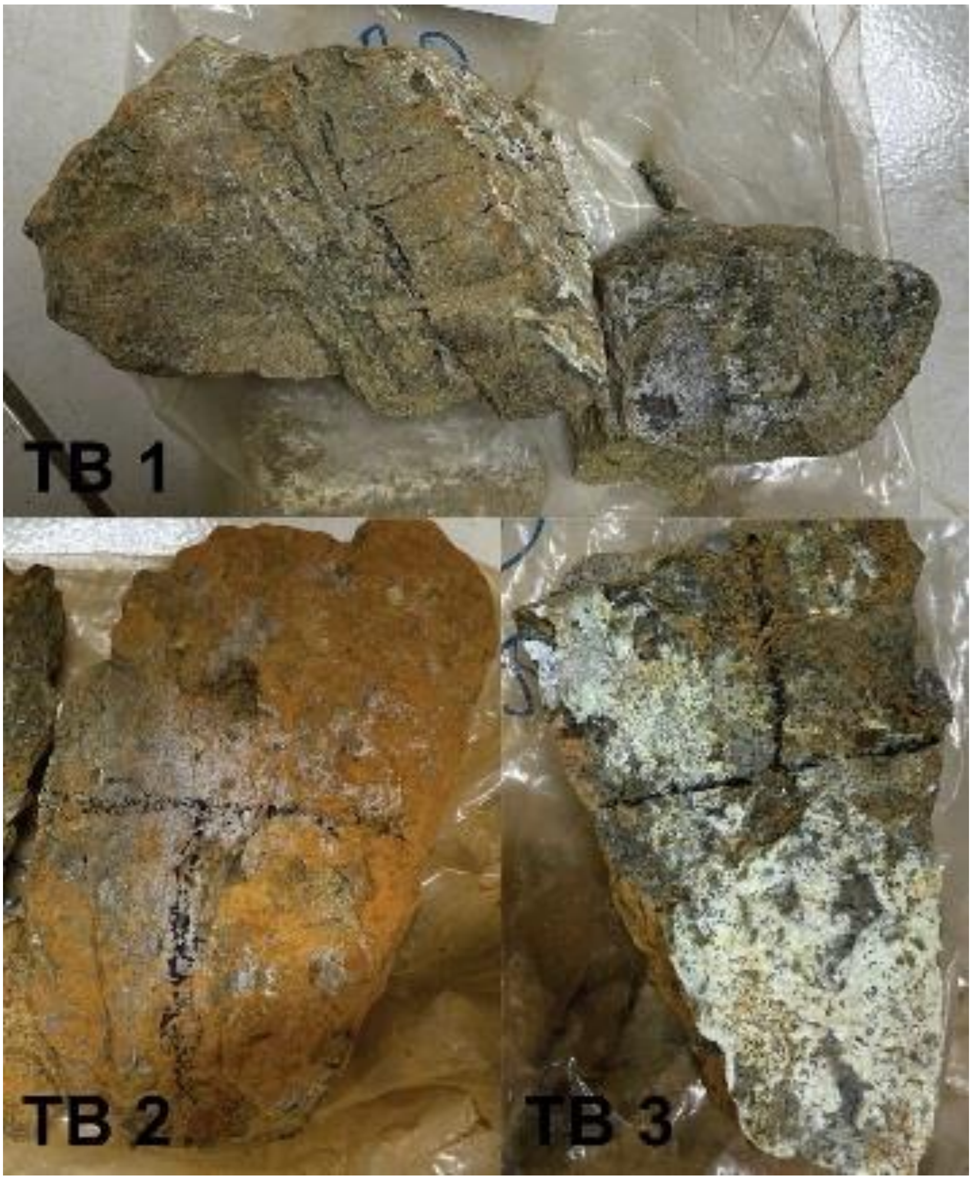

Fig 6. Megascopic Appearance of Dunite Rock Samples

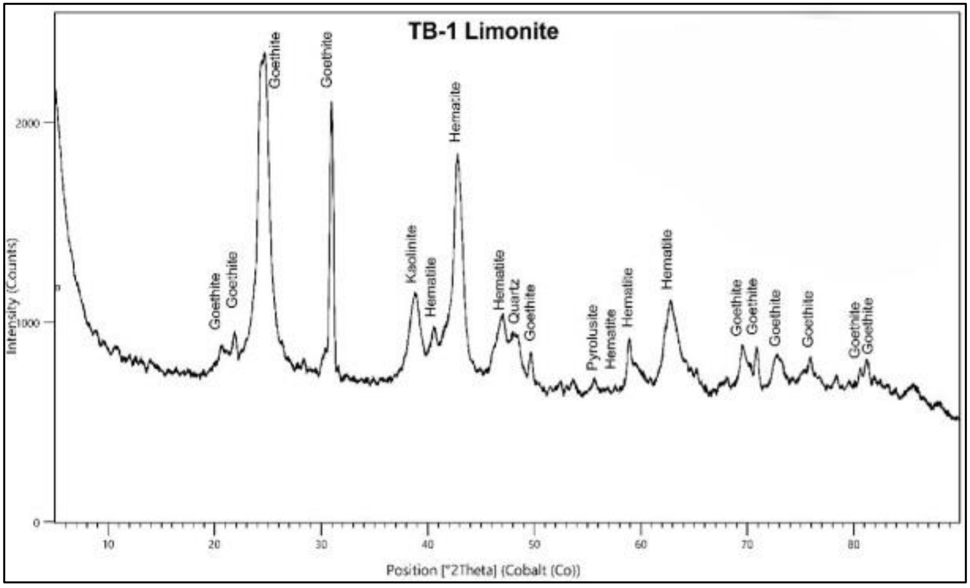

Fig 7. XRD Difactogram Graph of TB-1 Sample in the Limonite Zone

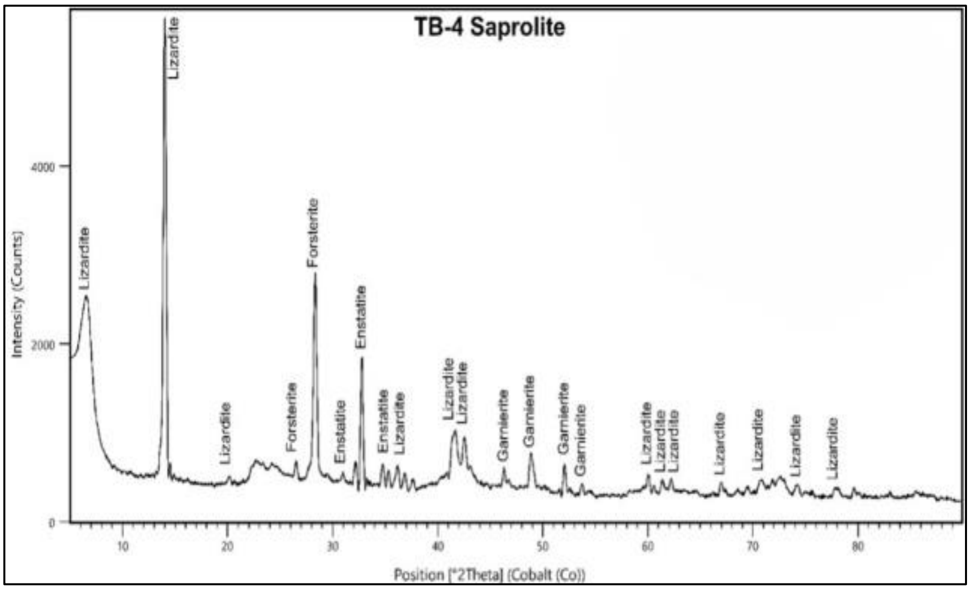

Fig 8. XRD Difactogram Graph of TB-4 Sample in the Saprolite Zone

Based on the results of XRD analysis of the limonite zone of samples TB-1 and TB-4, the results showed the presence of hematite and goethite minerals that dominate. In addition, other minerals such as quartz, pyrolusite, kaolinite, and lithioporite were also found in minor quantities. The dominant presence of hematite and goethite in the limonite zone can be explained by the geochemical conditions in this zone (Widiyandari et al., 2022). The limonite zone was formed as a result of intensive weathering processes, both chemically and physically, influenced by tropical climate factors, namely high rainfall, temperature, and hydrothermal fluid activity. At this stage, elements such as magnesium (Mg), calcium (Ca), and silica (Si) tend to dissolve and undergo a leaching process, thus moving to deeper zones (towards saprolite and bedrock).

Meanwhile, iron (Fe) is relatively immobile under highly oxidative conditions, so it remains in the limonite zone and contributes to the formation of Fe-oxide minerals such as hematite and goethite. This process is also supported by the low pH caused by rainwater which accelerates the dissolution of elements in unstable minerals in the host rock (bedrock) (Imalianda et al., 2025). Thus, these conditions create an excellent environment for the formation of Fe-rich minerals, such as hematite and goethite, as well as other secondary minerals such as pyrolusite which appears as an indicator of further oxidation of Fe ions. Furthermore, in the saprolite zone, XRD results from samples TB-1 and TB-4 show the presence of serpentine minerals such as lizardite and antigorite, forsterite from the olivine group, and nickel-rich minerals such as garnierite and enstatite from the orthopyroxene group.

This analysis strengthens petrographic observations and provides more specific mineral names. The presence of lizardite and antigorite indicates serpentinization, a reaction between fluids and mafic minerals such as olivine and pyroxene that forms serpentine minerals at low temperatures and pressures. This process also involves changes in chemical composition through water infiltration. Garnierite, a characteristic of Mg-hydrous silicate nickel deposits, forms due to the downward migration of dissolved silica during weathering, which then forms a secondary enrichment zone. The relationship between garnierite, forsterite, and enstatite illustrates the mineralogical evolution during the lateritization process, where primary minerals such as forsterite and enstatite undergo weathering and release Mg and Ni, which then form garnierite as a secondary mineral through substitution (Prinaldi et al., 2024).

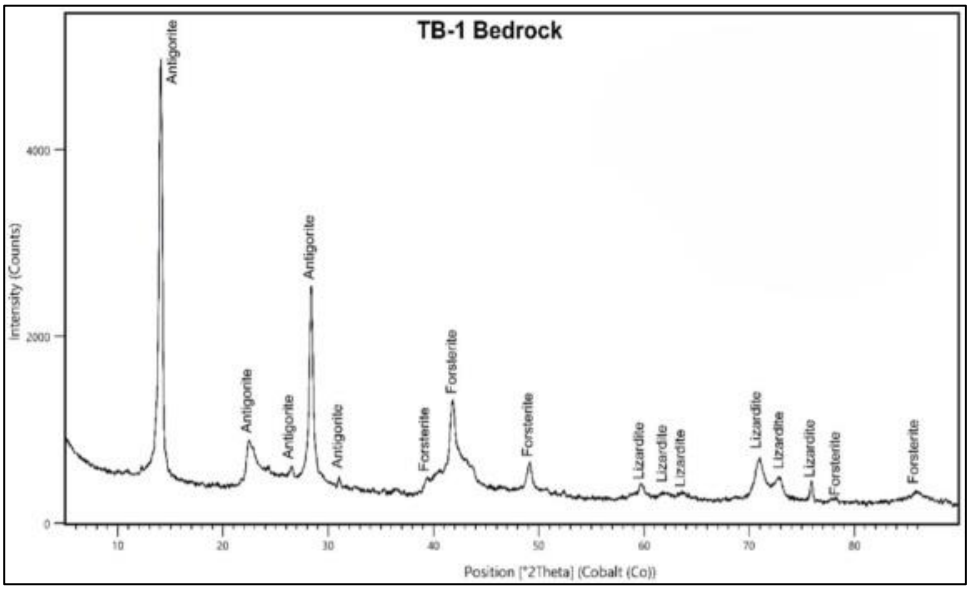

Fig 9. XRD Difactogram Graph of TB-1 Sample in the Bedrock Zone

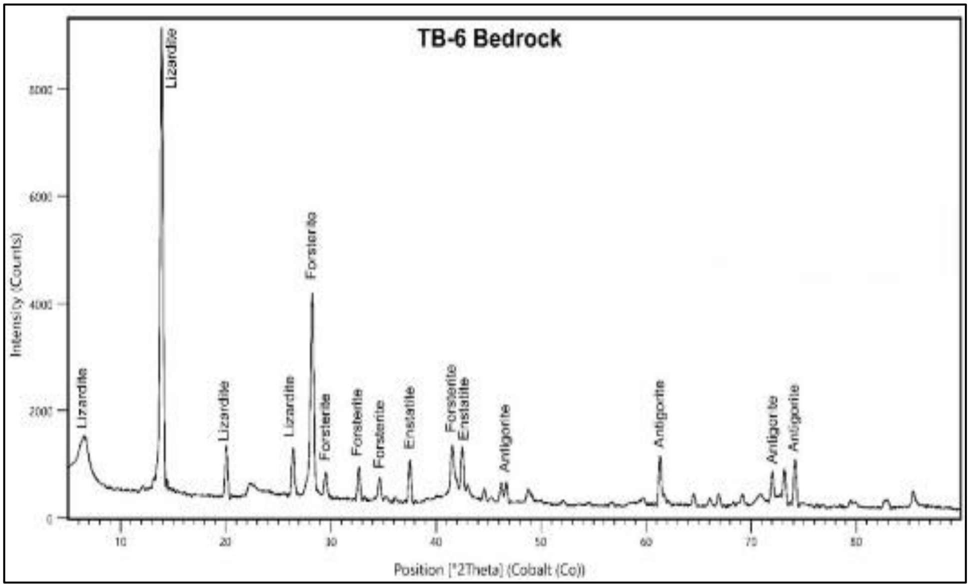

Fig 10. XRD Difactogram Graph of TB-6 Sample in the Bedrock Zone

In the bedrock zone of samples TB-1, TB-2, TB-4, and TB-6, XRD analysis revealed the presence of serpentine minerals such as lizardite and antigorite, forsterite from the olivine group, enstatite from orthopyroxene, and diopside from clinopyroxene. The presence of these primary minerals is related to the origin of ultramafic rocks such as dunite and harzburgite, which form from fractional crystallization of Mg-rich magmas in the upper mantle to oceanic crust environment. These ultramafic rocks are rich in Mg and Ni but poor in silica. The Ni content is uneven, with forsterite having the highest content (0.2–0.4%), while enstatite and diopside contain less Ni (0.05–0.2%).

Ultramafics that have undergone serpentinization generally produce lateritic nickel deposits that are richer than fresh or highly serpentinized rocks, which explains why Ni levels in the saprolite zone can reach up to 5.32 wt%.

3.2 Geochemical Characteristics of Laterite

Nickel laterite deposits in the study area are generally divided into several zones: overburden, limonite, saprolite, and bedrock, each of which can be distinguished based on its physical condition, color, and the type of mineral constituents.

Serpentinization processes transform primary minerals into serpentine such as lizardite and antigorite, the extent of which influences the formation of laterite nickel deposits. Medium serpentinization (40–60%) increases porosity and the movement of Ni-rich fluids, while high serpentinization (>80%) reduces permeability and binds Ni in inert serpentine structures. Therefore, the limonite zone rocks are redder due to the dominance of Fe-oxide minerals, followed by the saprolite zone which exhibits a softer texture and is rich in nickel, and the bedrock zone as the bedrock. The physical and visual characteristics of this zonal division are clearly visible. Based on statistical geochemical analysis (1), the saprolite zone has the highest average Ni content of 2.61 wt%, while Co elements are more concentrated in the limonite zone with an average of 0.14 wt%. The distribution of these elements reflects the geochemical evolution process of laterite which is controlled by element mobility during the weathering of ultramafic rocks (Konopka et al., 2022).

Tabel 1. Statistical Description of Geochemical Data from Each Zone

Zona		Fe_pct	MgO_pct	Ni_pct	SiO2_pct	CaO_pct	Co_pct
Bedrock	Minimum	4.17	24.41	0.25	12.30	0.01	0.01
	Maximum	37.27	40.27	1.29	42.57	2.78	0.10
	Mean	9.35	33.67	0.59	35.59	0.87	0.03
	Median	6.62	35.14	0.49	37.80	0.42	0.02
	Standard Deviation	8.12	4.14	0.31	7.20	0.84	0.02
Limonit	Minimum	8.64	0.01	0.76	1.41	0.02	0.01
	Maximum	53.10	31.61	1.80	41.20	1.78	0.35
	Mean	39.40	4.18	1.49	11.49	0.24	0.14
	Median	41.72	1.52	1.52	7.56	0.11	0.14
	Standard Deviation	10.70	7.35	0.22	11.49	0.36	0.07
	Minimum	6.58	0.01	1.76	4.55	0.04	0.01
	Maximum	44.62	31.66	5.32	53.22	2.27	0.35
Saprolit	Mean	20.38	15.25	2.82	30.41	0.72	0.07
	Median	13.91	17.99	2.61	35.73	0.55	0.05
Standard Deviation		11.46	9.52	0.82	12.54	0.56	0.06

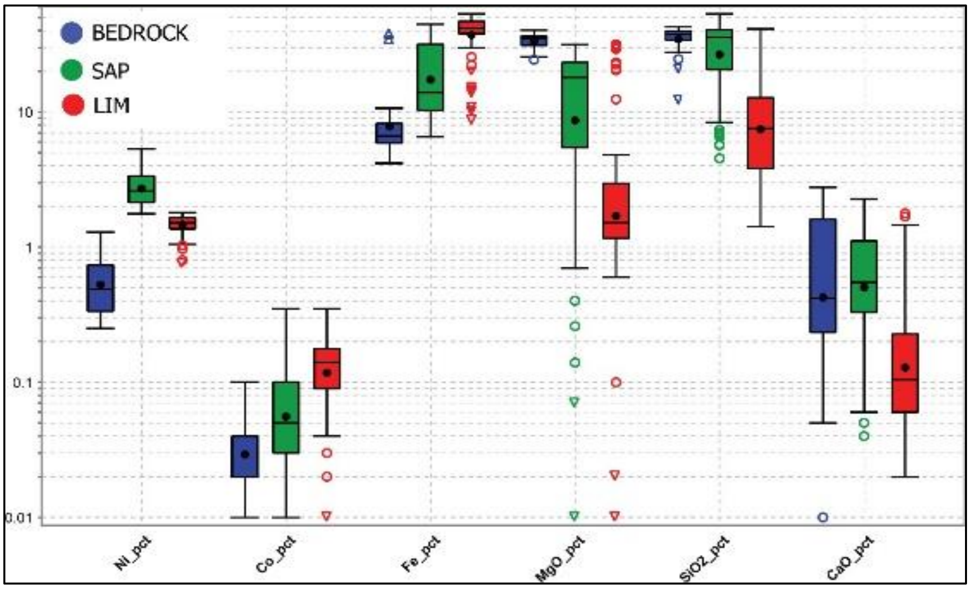

Fig. 11 Box Plot of Elements and Compounds for each Laterite Zone

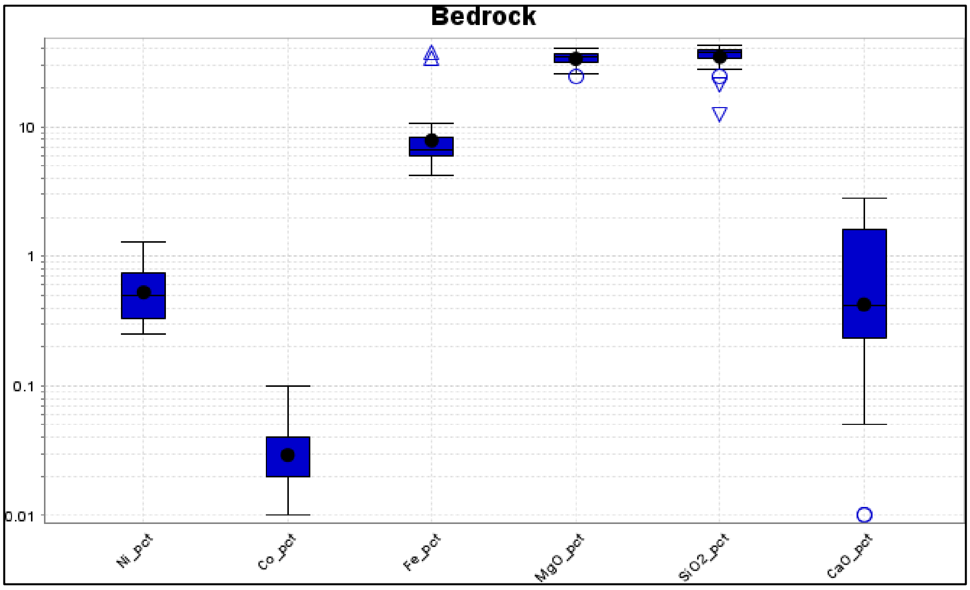

Fig. 12 Box Plot in Bedrock Zone

Elements with high mobility such as SiO_2, MgO, and CaO tend to be leached from the upper zone and move to the lower zone, while elements with low mobility such as Fe and Co are left behind and enriched.

Interaction with groundwater and the presence of more soluble Mg. Silica (SiO_2), which has high mobility, dissolves in slightly acidic environments, and tends to reaccumulate in the form of silica veins in both bedrock and saprolite zones (Maharani & Muin, 2023). MgO is also high in the bedrock zone because it is a major component of olivine and pyroxene minerals, while non-mobile Fe accumulates in limonite as goethite and hematite. The high Ni content in saprolite is also due to reprecipitation through substitution of Mg by Ni in secondary minerals such as garnierite.

Co, initially present in olivine and pyroxene, partially dissolves during weathering but is then adsorbed by Fe-oxide minerals in the limonite zone due to its limited mobility, resulting in co-enrichment with Fe.

The distribution of elements and compounds in the laterite profile is also depicted in the element box plot for each zone, while the residual (Fe and Co) and supergene (Ni) enrichment patterns are displayed in the downhole graph of drill point TB-1, which shows high Fe and Co contents in limonite and high Ni contents in saprolite (up to 4.65 wt%), while SiO_2 and MgO are very low in the limonite zone due to leaching. Correlations between elements were analyzed through the Pearson correlation matrix, showing that in the limonite zone, Co is moderately positively correlated with Fe (0.48) but negatively with other elements due to similar non-mobile properties, while SiO_2, MgO, and CaO are positively correlated with each other due to high mobility and co-leaching in the residual limonite zone (Fig 13).

While semi-mobile elements such as Ni undergo supergene enrichment in the saprolite zone due to the saprolite zone, Co and Fe have a strong correlation (0.73), while Ni is positively correlated with SiO_2 (0.31), which reflects the binding of Ni in secondary silicate minerals such as garnierite or serpentine under neutral-alkaline pH conditions and reductive environments (Golightly, 2010). In contrast, the correlation between Ni and Co in the limonite and saprolite zones tends to be negative and weak because the enrichment mechanisms of both are different. Overall, the distribution patterns of elements and the weathering processes that control the mobility, adsorption, and enrichment of these elements are key to understanding the nickel laterite system in the study area.

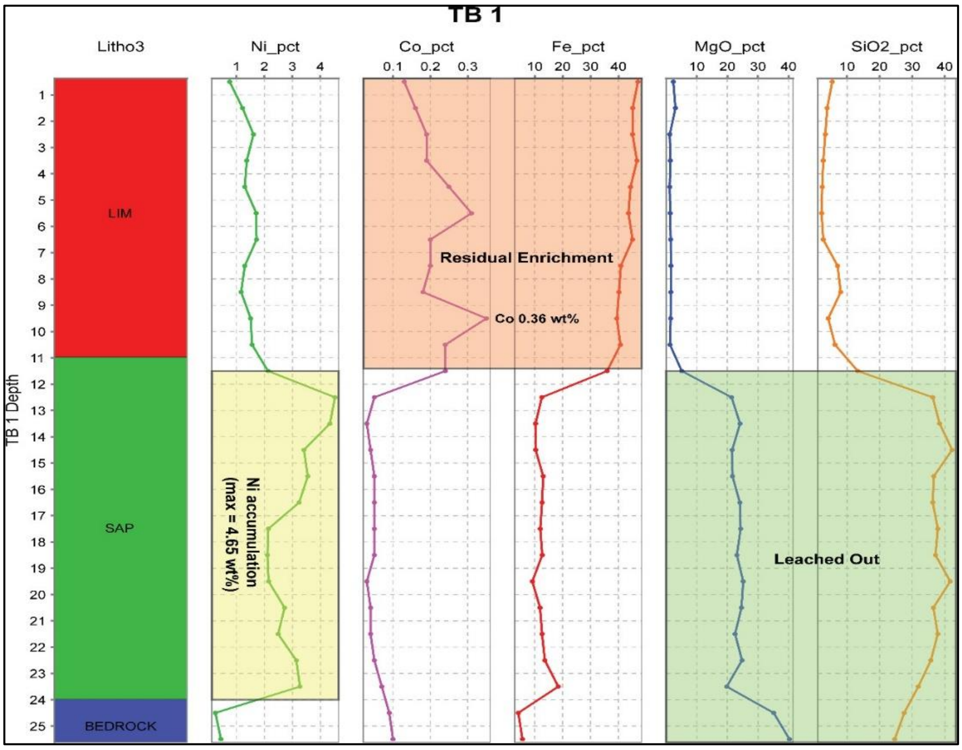

Fig 13. Downhole Graph Showing Residual and Supergene Enrichment at Drill Point TB 1

Tabel 2. Matriks Korelasi pada Zona Limonit

Element	Co	Ni	Fe	MgO	SiO2	CaO
Co	1					
Ni	-0.02	1				
Fe	0.48	-0.11	1			
MgO	-0.48	0.17	-0.83	1		
SiO2	-0.52	-0.05	-0.94	0.74	1	
CaO	-0.57	0.18	-0.78	0.73	0.74	1

Tabel 3. Matriks Korelasi pada Zona Saprolit

Element	Co	Ni	Fe	MgO	SiO2	CaO
Co	1					
Ni	-0.29	1				
Fe	0.73	-0.31	1			
MgO	-0.68	0.19	-0.94	1		
SiO2	-0.71	0.31	-0.97	0.85	1	
CaO	-0.47	0.04	-0.65	0.58	0.61	1

3.3 Factors Controlling Ni-Co Abundance

Based on the probability plot graph (Figure IV.21), there is a fairly clear pattern in the distribution of Ni in each laterite zone. This is evident from the relatively high accumulation of Ni in the saprolite zone (average Ni 2.82 wt%), followed by a moderate Ni content in the limonite zone (average Ni 1.49 wt%), and a low Ni content in the bedrock (average Ni 0.59 wt%). Ni is more concentrated in the saprolite zone than in the limonite zone or other zones in the laterite profile due to supergene enrichment and element mobility. Ni bound in the structure of primary silicate minerals such as olivine is released during weathering but is not leached out due to its stability at neutral to alkaline pH.

In the saprolite zone, Ni undergoes secondary precipitation and forms minerals such as garnierite due to interactions with silica-rich solutions (Wahab et al., 2024). The Ni enrichment process in the saprolite zone is also influenced by the presence of serpentine minerals such as lizardite and antigorite, which are the result of serpentinization of primary minerals in ultramafic rocks. The variability of Ni levels in the saprolite zone also reflects the heterogeneity in the degree of serpentinization in the bedrock and the intensity of the weathering process (Golightly, 2010). Meanwhile, in the limonite zone, which is dominated by Fe-oxide minerals such as goethite and hematite, high oxidation conditions make Ni less stable, resulting in some Ni leaching out to deeper layers (the saprolite zone). Goethite, as the primary Fe-oxide mineral in the limonite zone, has a limited Ni^{2+} adsorption capacity due to its positive surface charge at pH <8, making Ni more readily soluble in acidic fluids (Jurnal et al., 2025).

Fe tends to accumulate in the limonite zone due to its relatively immobile nature under various pH conditions, particularly under the high oxidation conditions prevalent in this zone. Meanwhile, for the Co element, it is generally enriched in the limonite zone (average Co 0.14 wt%), but is also distributed in the saprolite zone (average Co 0.07 wt%). Co enrichment occurs in the limonite zone due to the limited mobility of the Co element, while the presence of Co in the saprolite zone is due to it being a residual element that is bound together with clay minerals (Butt & Cluzel, 2013). This comparison of the distribution patterns of Ni and Co reflects the differences in the geochemical behavior of the two elements during the lateritization process, where Co has a higher affinity for minerals rich in Mn and Fe under high oxidation conditions that are dominant in the limonite zone.

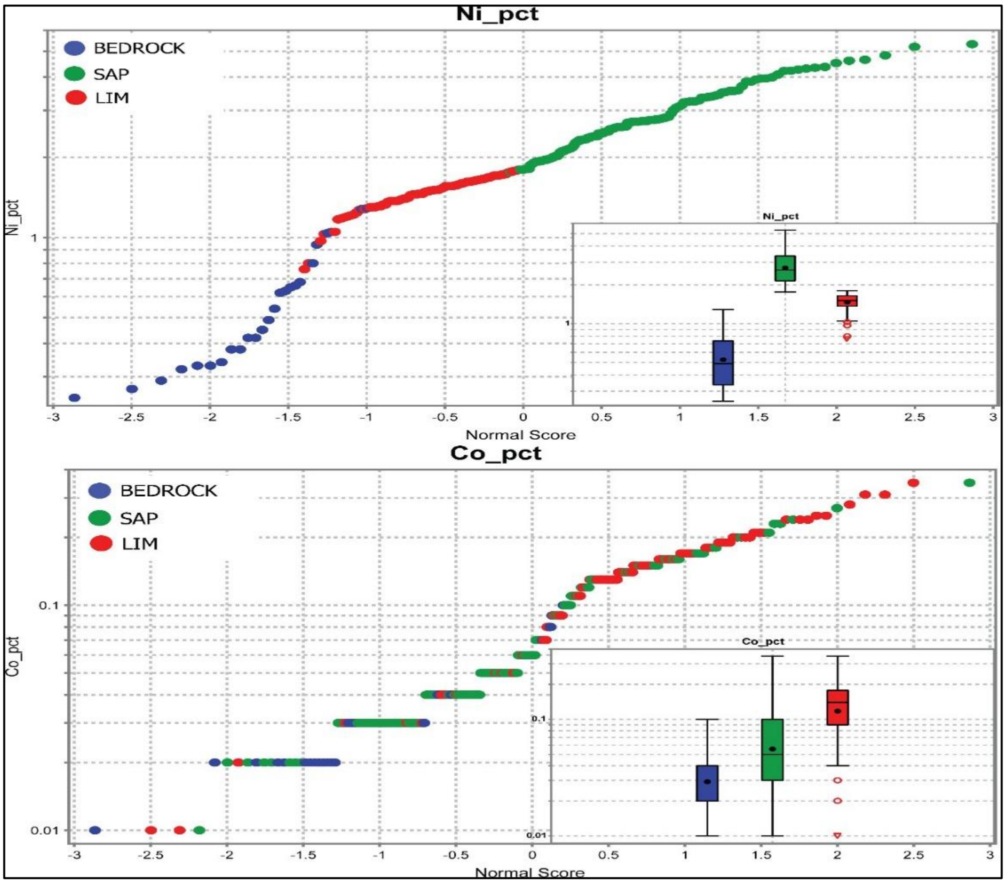

Fig 14. Probability Plot and Box Plot on Ni and Co Elements in Each Laterite Zone

3.4 Nickel Laterite Deposit Type

Nickel laterite deposits are generally divided into three types: clay silicate, oxide, and hydrous Mg silicate (Ninasafitri et al., 2023). This classification is based on the presence of nickel ore in the laterite profile. In the clay silicate type, Ni is generally present or adsorbed on clay minerals and is usually enriched in the transition zone. In the oxide type, Ni is generally enriched in the limonite zone and is closely associated with Fe-oxide minerals such as goethite and hematite. In the hydrous Mg silicate type, Ni is enriched in the saprolite zone and is found in garnierite minerals. The type of nickel laterite deposits in the study area belongs to the hydrous Mg silicate type. This is characterized by Ni enrichment occurring in the saprolite zone and based on XRD analysis results, garnierite minerals were found. Garnierite in the saprolite zone is a secondary mineral resulting from Ni-rich serpentine alteration, formed under neutral-alkaline pH conditions and high silica activity (Soh Tamehe et al., 2024). Olivine-rich ultramafic rocks such as dunite tend to form garnierite-rich saprolite deposits, while pyroxene-rich rocks produce oxide-type laterites (Putri Wirman et al., 2021). To see the Ni enrichment pattern in the saprolite zone, see Figure IV.25, which consistently shows high levels of Ni accumulation.

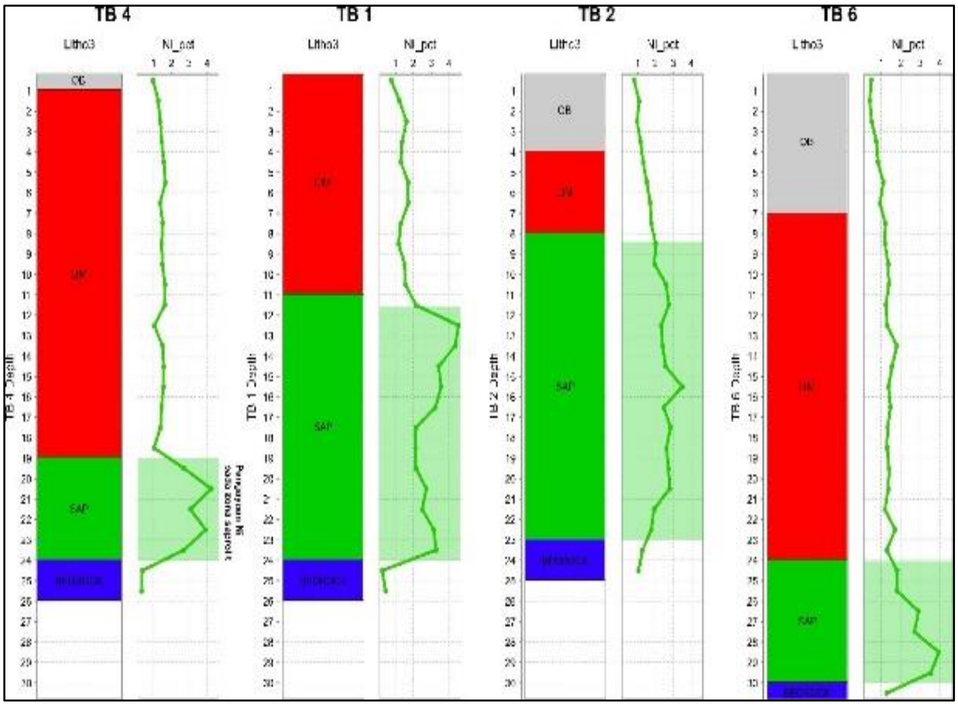

Fig 15. Downhole Graph of Several Drill Points Showing Ni Enrichment in the Saprolite Zone

3.5 Abundance Controlling Factors of Ni–Co

The profile of laterite nickel deposits at the research site shows a complex and distinctive vertical zoning pattern, consisting of four main zones stratigraphically from top to bottom, namely overburden, limonite, saprolite, and bedrock, each of which is formed as a result of intensive weathering of ultramafic rocks and shows different mineralogical and geochemical characteristics. The overburden zone is the outermost cover layer consisting of advanced weathered soil mixed with organic material and loose residues, generally does not contain significant economic elements and acts as a protector for the zone below. The limonite zone below is characterized by a deep red-brown color due to the dominance of goethite and hematite minerals, which are iron weathering products from olivine and pyroxene, and contains a significant cobalt (Co) content of an average of 0.14 wt%, with Co accumulation thought to occur through the process dsorption and ionic substitution in the Fe-oxide structure, this zone also visually and geochemically shows an increase in total Fe_2O_3 content to >48 wt% and a decrease in MgO, CaO, and SiO_2 elements due to intensive vertical leaching by tropical acidic water.

Furthermore, the saprolite zone located below the limonite is the main horizon where nickel (Ni) enrichment occurs, characterized by a softer soil texture and a lighter green-brownish color, as well as the presence of silicate minerals such as serpentine and garnierite, which are the main hosts of nickel with an average content of 2.61 wt% and reaching a maximum of 4.65 wt%. As shown, Ni enrichment in the saprolite zone is believed to occur due to lateritization and supergene enrichment processes, where Ni ions carried by meteoric solutions from the upper zone replace Mg^{2+} in the structure of secondary silicate minerals and then accumulate in the form of new nickel-rich minerals.

Tabel 4. Statistical Description of Ni Elements Based on Bedrock Type in Each Laterite Zone of Dunite Rock

Name	Count	Mean	Standard deviation	Coefficient of variation	Variance	Minimum	Median	Maximum
Dunite	72	1.935	0.928	0.480	0.861	0.25	1.76	4.52
Bedrock	8	0.678	0.360	0.531	0.129	0.25	0.62	1.28
Limonit	24	1.460	0.275	0.188	0.075	0.76	1.51	1.77
Saprolit	35	2.687	0.683	0.254	0.466	1.76	2.57	4.52
Harzburgite	91	1.863	0.942	0.505	0.887	0.34	1.57	5.2
Bedrock	4	0.668	0.439	0.657	0.192	0.34	0.38	1.29
Limonit	48	1.454	0.192	0.132	0.037	0.97	1.46	1.8
Saprolit	31	2.936	0.771	0.262	0.594	1.81	2.76	5.2

Tabel 5. Statistical Description of Co Elements Based on Bedrock Type in Each Laterite Zone

Name	Count	Mean	Standard deviation	Coefficient of variation	Variance	Minimum	Median	Maximum
Dunite	72	0.110	0.087	0.788	0.007	0.02	0.07	0.35
Bedrock	8	0.048	0.030	0.634	0.001	0.02	0.03	0.1
Limonit	24	0.167	0.098	0.588	0.010	0.03	0.18	0.35
Saprolit	35	0.087	0.071	0.807	0.005	0.03	0.06	0.35
Harzburgite	91	0.115	0.059	0.515	0.003	0.01	0.13	0.27
Bedrock	4	0.043	0.021	0.485	0.000	0.02	0.04	0.07
Limonit	48	0.131	0.047	0.360	0.002	0.01	0.14	0.24
Saprolit	31	0.094	0.072	0.769	0.005	0.01	0.06	0.27

The lowest zone is bedrock consisting of fresh ultramafic rocks, predominantly olivine and pyroxene, with a geochemical composition high in MgO and SiO_2, and is the main source of all metal elements in the weathering zones above it. The characteristics of each of these zones are clearly visible in the stratigraphic cross-section of the drill and reflected in the element distribution boxplot, which shows that elements with high mobility such as SiO_2, MgO, and CaO have a tendency to decrease significantly upward due to the leaching process, while non-mobile elements such as Fe and Co experience a relative enrichment in the limonite zone. The results of the element correlation analysis using the Pearson matrix as shown in Tables IV.2 and IV.3 reinforce this distribution pattern, where in the limonite zone, a moderate positive correlation between Fe and Co ($r = 0.48$) reflects a strong link between the two elements in the iron oxide structure, while a strong positive correlation between SiO_2, MgO, and CaO indicates that these elements experience high mobility and are transported simultaneously through groundwater from top to bottom. On the other hand, in the saprolite zone, the correlation between Fe and Co increases to a strong level ($r = 0.73$) indicating continued accumulation in that horizon, but the correlation between Ni and SiO_2 is only around $r = 0.31$, indicating that although Ni is present in silicate minerals, its association is more influenced by ion replacement reactions and not simply the presence of silicates themselves. Another interesting point is the negative correlation between Ni and Co in both the limonite and saprolite zones, indicating that they are distributed through different mechanisms: Co tends to associate with Fe-oxide minerals in the upper weathering zone, while Ni migrates and is fixed in the lower weathering zone within silicate structures, making it unlikely that both accumulate in the same zone in high concentrations. This is clarified in the vertical distribution graph of elements from the TB-1 drill, which shows that Fe and Co contents peak in the limonite zone, while Ni reaches its highest concentration in the saprolite zone, with the SiO_2 and MgO graphs showing a sharp decrease from the bottom to the top of the zone, supporting the hypothesis of vertical leaching and element remobilization. Overall, the combination of stratigraphic data, vertical element distributions, correlations between elements, and weathering and chemical reactions in a humid tropical environment indicates that the laterite nickel deposits at this site are the result of a complex geochemical evolution influenced by ultramafic lithology, tropical climate, relative element mobility, and host mineral stability, which together produce regular chemical and mineralogical zoning and provide a strong basis for the exploration and development of sustainable nickel-cobalt resources.

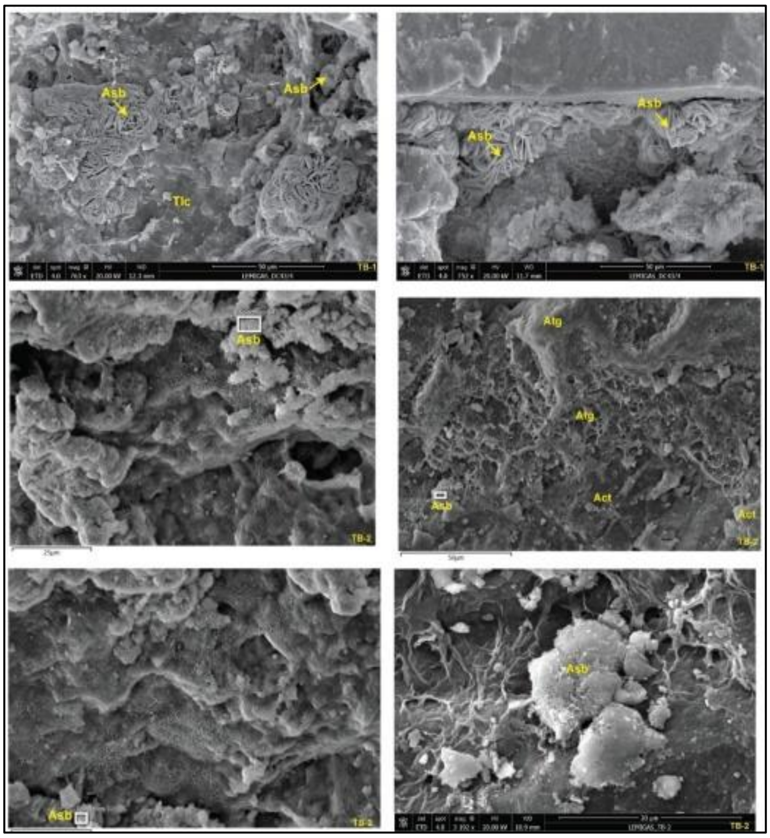

Fig. 16 Backscattered Electrons (BSE) Photo Showing Some Minerals Found in Rock Samples (Asb: Asbolane; Atg: Antigorite; Act: Actinolite; Tlc: Talc)

4. Thank You

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5. Conclusion

This study shows that laterite nickel deposits on Pakal Island have clear vertical zoning. The geological conditions of the study area indicate the presence of two main rock units based on petrographic observations of bedrock samples, namely the Dunite and Harzburgite Rock Units which are regionally Cretaceous in age. The geochemical characteristics of laterite nickel deposits show that the highest Ni element is found in the saprolite zone (average 2.82 wt%), followed by limonite (1.49 wt%) and bedrock (0.59 wt%), while the Co element is concentrated in the limonite zone (average 0.14 wt%), followed by saprolite (0.07 wt%) and bedrock (0.03 wt%). Compounds such as SiO_2, MgO, and CaO tend to be distributed more in saprolite and bedrock, while Fe accumulates in limonite. Based on the dominance of Ni enrichment in the saprolite zone and the presence of garnierite minerals, this deposit is classified as a hydrous Mg silicate type. Co enrichment is controlled by geological factors such as host rock type, degree of laterization and serpentinization, topographic conditions, and the abundance of goethite minerals; where samples from dunite rocks, with high serpentinization and laterization, and gentle topography, show higher Co levels. In addition, the positive correlation between goethite and Co levels, as seen at drill point TB-1, confirms that Asbolane minerals play a role as the main carrier of Co elements in this study location. Based on these results, it is recommended that Ni-Co resource exploration activities in this area be focused on the limonite zone for cobalt potential and the saprolite zone for nickel, considering lithological conditions and weathering levels as the main factors in sustainable resource evaluation.

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