Identification of Lateritic Nickel Deposits Potential in the Kokoe Area, Kabaena Island, Central Buton Regency, Southeast Sulawesi Province, Indonesia

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Abstract

The study is situated in the Kokoe Region of Central Buton Regency, Southeast Sulawesi, specifically in the southern part of Kabaena Island. Its primary objective is to assess the potential of nickel laterite in the designated area. The research methodology involved microscopic analysis of bedrock using a polarizing microscope, examining the drilling data, including logging descriptions, and utilizing XRF geochemical analysis (Ni, Fe, Al\textsubscript{2}O\textsubscript{3}, Co, Mg, and SiO\textsubscript{2}) from 32 drilling sites. Both elementary grade and laterite profiles were visualized using Strater 5 software to simplify the representation of laterite profiles. Petrographic analysis divided the bedrock into two lithological units: serpentinized lherzolite and serpentinite. The laterite profiles in the study area were classified into four types: type A, type B, type C, and type D. Type A profiles consist of bedrock, saprolite, and limonite layers covered by clay and colluvium. Type B profiles lack limonite and instead exhibit saprolitic rock and rocky saprolite layers on top of the bedrock. Type C profiles comprise bedrock, saprolitic rock, rocky saprolite, limonite, and topsoil layers. Type D profiles contain three zones, namely bedrock, colluvium, and clay, but lack limonite and saprolite layers. Among the four profile types, type A and type C profiles show promising potential due to higher average grades of Ni and thicker saprolite zones compared to the type B and type D profiles.

Keywords: Potential; Nickel; Laterite; Exploration; Kabaena

1. Introduction

Nickel (Ni) is an important metal with a global consumption of approximately 2 million tons per year, which has significantly grown since the 1940s (Mackey, 2011; Awadh, 2015). Regarding reserves, as of the latest data in 2021, the world's nickel reserves are estimated to be around 95 million metric tons. Amongst this, Indonesia and Australia hold the largest reserves, with 21 million metric tons each, followed by Brazil with 16 million metric tons and Russia with 16 million tons (Garside, 2022). Nickel metal can be derived from sulfide ores in Australia, Canada, China, Russia, Brazil, and South Africa, as well as from laterite deposits in New Caledonia, Cuba, Indonesia, and the Philippines (Elias, 2002).
Amongst these two types of deposits, laterite deposits are currently more attractive for production due to the depletion of high-grade sulfide deposits (Awadh, and Nejbert, 2016).

Lateritic nickel deposits are formed through intensive chemical and mechanical weathering of ultramafic rocks exposed at the surface under specific climatic, topographic, lithological, and geological structural conditions (Freyssinet et al., 2005; Butt and Cluzel, 2013). In Indonesia, lateritic nickel deposits are distributed in several regions, with the most significant potential being on Sulawesi Island. This can be attributed to the extensive occurrence of ultramafic rocks known as the East Sulawesi Ophiolite (ESO) on the island (Kadarusman et al., 2004). The ultramafic rocks occupying the ESO are concentrated along the Eastern Arm to the Southeastern Arm of Sulawesi (Fig. 1a), resulting from the interaction between three tectonic blocks: Sundaland, fragmented Sula Spur, and the Australian continent (Fig. 1b). More specifically, ultramafic rocks in the eastern arm of Sulawesi are found in the Luwuk Banggai and Morowali regions, while in the Southeastern Arm of Sulawesi, ultramafic rocks are prominent in the North Konawe, Kolaka, South Konawe, and Kabaena Island regions (Kadarusman et al., 2004).

This research is conducted on Kabaena Island, specifically in the Kokoe area of Central Buton Regency, Southeast Sulawesi, Indonesia. The geological map in Fig. 2 shows that this area is...
predominantly characterized by clay and colluvium. However, after exploration drilling was conducted, it was revealed that weathered ultramafic rock (laterite) was discovered beneath the clay and colluvium. This fact makes this research intriguing to pursue because the studied lateritic nickel deposits in Indonesia thus far are generally profiles that are not covered by clay and colluvium (e.g. Konopka et al., 2022; Farrokhpay et al., 2019; Hasria et al., 2019; Kusuma et al., 2019; Aribowo et al., 2018; Ilyas et al., 2016; Fu et al., 2014).

Fig. 2. Geological map of Kabaena Island (modified from Simandjuntak et al., 1993). The surface lithology distribution in the study area (red box) is presented in Fig. 3 in more detail.

2. Geological Setting

Kabaena Island is located in the southern part of the Southeast Sulawesi Island. It consists of continental fragments composed of metamorphic rock complexes and ophiolitic rocks, predominantly ultramafic rocks (Fig. 1). Referring to the geological map of the Kolaka sheet (Simandjuntak et al., 1993), Kabaena Island is composed of several rock formations, ranging from the oldest to the youngest: Ultramafic Complex (Ku), Pompangeo Complex (MTpm), Matano Formation (Km), Langkowala Formation (Tml), and Alluvium (Qa) (Fig. 2). Ku, which is of Cretaceous age, is part of the ophiolite and consists of harzburgite, dunite, wehrlite, serpentinite, gabbro, basalt, dolerite, diorite, metamafic, amphibolite, magnesite, and locally rodingite. Km is composed of Late Cretaceous limestone, including recrystallized and folded limestone, radiolarian chert, and slate. MTpm, ranging from Late Cretaceous to Paleocene, consists of metamorphic rocks such as mica schist, glaucophane schist, amphibolite schist, chlorite schist, jasperoidal chert, gneissic schist, marble, and meta-limestone. In the Rumbia and Mendoke Mountains, mica schist from MTpm is known to host gold mineralization (Idrus et al., 2011). Tml is part of the Sulawesi Molasse, which is Miocene in age and is composed of conglomerate, sandstone, shale, and locally calcarenite. On the other hand, alluvium is a Holocene sedimentary deposit dominated by mud, clay, sand, gravel, and peat.
The geological map in Fig. 2 also shows dominant geological structures, including east-west trending thrust faults (Simandjuntak et al., 1993). These structures have caused the uplift of Ku over Km and MTpm. The thrust faults were formed due to the collision between ophiolitic rocks from the oceanic origin and the northern continental fragments of Australia during the Late Oligocene to Middle Miocene (Surono, 2013). Following this collision, extensional regimes led to a deep basin where the Sulawesi Molasse (Tml) was deposited (Panggabean and Surono, 2011).

The research area is located in Kokoe, in the southern part of Kabaena Island, and is composed of two rock formations, Ku and Qa. The exploration drilling results revealed that beneath Qa, the lithology of Sulawesi Molasse (Tml) and weathered ultramafic rocks from Ku are found. The presence of the Tml covering the ultramafic rocks is intriguing. Similar characteristics of lateritic nickel deposits covered by this type of formation have also been found in other areas, such as South Konawe, Indonesia (Raivel and Firman, 2020), Murrin Murrin, Western Australia (Elias et al., 1981), and Mirdita, Albania (Thorne et al., 2012). These areas have distinct characteristics of their respective deposit types, including the enrichment trend of nickel in their lateritic deposit profiles. Based on the above description, research on lateritic nickel deposits is necessary to assess the potential of lateritic nickel deposits in the Kokoe area.

3. Materials and Methods

This research was conducted in four stages: literature review, field data collection, laboratory analysis, and data processing and interpretation. The data collected consisted of logging descriptions from the exploration drilling at 32 borehole locations (Fig. 3). In the logging description stage, the laterite profiles were categorized into several types based on similarities in their layer composition. These laterite profile types were then visualized using Strater 5 software by drawing section lines passing through borehole points DHPG02, DHPG04, DHPG05, DHPG10, DHPG12, DHPG21, DHPG19, and DHPG18. Laboratory analysis included petrography and geochemistry. The petrographic analysis involved four samples of fresh or least altered rocks and aimed to determine the mineralogical characteristics of the bedrock. On the other hand, geochemical analysis using the XRF (X-ray fluorescence) method involved core samples collected at 1-meter intervals for each borehole point. The XRF instrument used for analysis was the epsilon 3XLE, where the main determined elements/oxides consisted of Ni, Fe, Al\(_2\)O\(_3\), Co, MgO, and SiO\(_2\).

![Fig. 3. Location map of the drilling points showing the distribution of surface lithology, bedrock lithology, and types of lateritic nickel deposit profiles in the research area. The inset map can be seen in Fig. 2.](image-url)
4. Results and Discussions

4.1. Characteristics of Bedrock

The research area was examined through microscopic observations of bedrock samples taken from 32 drilling points. The analysis revealed the presence of two distinct lithologies: serpentinized lherzolite and serpentinite. The southern part of the research area is predominantly occupied by serpentinized lherzolite. In contrast, serpentinite is more prevalent in the northern part (Fig. 3). To investigate these findings further, petrographic analysis was carried out on bedrock samples collected from four representative drilling points. Specifically, DHPG13 was selected to represent serpentinized lherzolite bedrock, while DHPG04, DHPG15, and DHPG20 were chosen to represent serpentinite.

4.1.1. Serpentinized Lherzolite

The serpentinized lherzolite described is a core sample obtained from drilling (Fig. 4a and 4b). Based on microscopic descriptions from petrographic analysis, the rock exhibits a range of absorption colors, from grayish to brownish-gray, and various interference colors, including yellow, blue, purple, and gray. It is a hypocrystalline rock (composed entirely of crystals) with a porphyritic texture, displaying euhedral to subhedral crystal forms. The minerals comprising this rock consist of primary minerals such as olivine (36%), orthopyroxene (15%), clinopyroxene (10%), and secondary minerals in the form of serpentine (34%), specifically lizardite and antigorite. Distinguishing between lizardite and antigorite can be challenging in thin sections as they exhibit similar interference colors.

![Fig. 4.](image)

Fig. 4. The appearance of serpentinized lherzolite in (a) the core box and (b) in the hand specimen sample. (c-d) Photomicrographs of serpentinized lherzolite showing mesh and hourglass textures. The rock is composed of minerals such as olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), antigorite (Atg), lizardite (Lz), and magnesite (Mgs) as observed under (c) cross-polarized light or XPL and (d) plane-polarized light, PPL.
The main differentiating factor lies in their crystal forms. Lizardite generally exhibits very fine crystal sizes, while antigorite often displays mica-like (micaceous) forms and can form foliated mineral masses or occasionally exhibits a decussate texture (Mackenzie et al., 2017). Another mineral identified in veins is magnesite (5%).

In general, olivine is present in the serpentine matrix as rounded relics with numerous fractures that create a mesh texture (Fig. 4c and 4d), and it is filled with lizardite-type serpentine. Not only olivine, orthopyroxene and clinopyroxene minerals exhibit fractures filled with serpentine veins, forming a mesh texture (Fig. 4c and 4d). Magnesite, a type of magnesium carbonate mineral, is found in the observed serpentinized lherzolite sample and appears as a filling mineral within the veins (Fig. 4c). The serpentine minerals are not only present in the mesh texture as fillings in fractures but also occur as replacement minerals in some parts of olivine, orthopyroxene, and clinopyroxene minerals, giving rise to pseudomorphic or hourglass textures in certain areas.

4.1.2. Serpentinite

The observed serpentinite is a core sample (Fig. 5a). Macroscopically, this rock exhibits a relatively greener color compared to serpentinized lherzolite (Fig. 5b). Based on microscopic observations, serpentinite displays brown to colorless colors in PPL observation and yellow and gray in XPL observation. This rock is also hypocrystalline, with its constituent minerals appearing subhedral to anhedral shape. Generally, serpentinite is composed mainly of serpentine minerals (90%) and opaque minerals (10%). The colors of the primary minerals are no longer discernible. However, mesh textures indicate that this rock originated from olivine-rich ultramafic rock.

Fig. 5. The appearance of serpentinite in (a) core box and (b) thin section sample, as well as photomicrographs of serpentinite showing the presence of antigorite (Atg), chrysotile (Ctl), lizardite (Lz), and opaque minerals (Opq) under (c) XPL and (d) PPL observations.
The observed serpentine minerals are present as replacement minerals and as vein fillings. Lizardite, chrysotile, and antigorite are serpentine minerals composing this serpentinite. Lizardite tends to occur with very fine crystal size, replacing olivine minerals and filling vein spaces. Chrysotile appears with an asbestos texture. Meanwhile, antigorite exhibits a flattened shape with random orientation, forming an accurate texture (Fig. 5c). In addition to serpentine minerals, opaque minerals are also components of this rock, where they occur in the middle of the mesh texture and within fractures as veins along with lizardite (Fig. 5c and 5d). These opaque minerals are believed to be magnetite. This assumption is based on the common occurrence of magnetite as a secondary mineral within mesh-textured olivine (Bhilisse et al., 2019; Abdel-Rahman et al., 2022). Gahlan et al. (2006) mentioned that iron in magnetite is supplied by olivine during the serpentinization process.

4.2. Laterite Profile in the Research Area

Laterite profiles discussed in this study are based on logging descriptions of 32 borehole points in the low relief of the research area. The identified layers in the laterite profile, from bottom to top, consist of 7 layers: bedrock, saprolitic rock, rocky saprolite, saprolite, limonite, colluvium, clay, and topsoil (Fig. 6). However, none of the borehole points shows a complete layer sequence. Based on the arrangement of profile layers in these borehole points, the laterite profiles in the research area are classified into four types: Type A, Type B, Type C, and Type D. Type A profiles are composed, from bottom to top, of bedrock, saprolite, and limonite, with these three layers covered by clay-sized material and colluvium. Type B profiles are characterized by the absence of limonite in the profile. At drill point DHPG 19, layers of saprolytic rock and rocky saprolite were discovered above the bedrock (Fig. 6). Type C profiles consist of bedrock, saprolitic rock, rocky saprolite, limonite, and topsoil layers. On the other hand, Type D profiles are profiles composed of only three layers: bedrock, colluvium, and clay, lacking the limonite and saprolite layers (Fig. 6). In detail, each type of profile is described as follows.

![Fig. 6. The 2D cross-section correlating the profiles of type A, type B, type C, and type D](image)

4.2.1. Type A Profile

Type A profile is characterized by layers covered by clay and colluvium (loose ultramafic fragments ranging from gravel to pebble-sized particles that are poorly sorted), limonite, saprolite, and bedrock.
Based on XRF geochemical analysis of the clay and colluvium zone, the percentage values of elements such as Ni, Fe, Al₂O₃, Co, and SiO₂ are relatively consistent from the early drill penetration, except for a slight increase of 40.08% in MgO when entering the colluvium material. The high values of MgO and SiO₂ in the colluvial material indicate that it consists of unweathered ultramafic rock (Ahmad, 2006). The limonite zone in this profile has a thickness of 2.90 meters and is composed of fine reddish-brown material consisting of oxide minerals such as goethite, hematite, and manganese oxides. This zone is highly weathered, and no original rock can be found as it has completely transformed into soil. The saprolite zone is located beneath the limonite zone and has a relatively thicker thickness of 3.70 meters, displaying a yellowish-green color. In this zone, fragments of ultramafic rock can still be found, although the texture and structure are difficult to identify. However, minerals such as serpentine, manganese oxide, goethite, and hematite can still be recognized by their colors. According to XRF geochemical analysis (Fig. 7), the Ni element undergoes enrichment within the saprolite zone, indicated by a significant increase in Ni percentage by 3.5%, gradually decreasing to 1.21% Ni as it approaches the bedrock zone.

Fig. 7. The borehole log of the type A profile represented by hole ID DHPG04. Mineral abbreviations: PX = pyroxene, OL = olivine, GTH = goethite, HMT = hematite, SER = serpentine, SIL = silica.
The bedrock, a gray-colored ultramafic rock, is composed of minerals such as pyroxene, olivine, and serpentine, and contains quartz veins filling the fractures at a drilling penetration depth of 5.8 meters. According to XRF geochemical analysis, as it enters the bedrock zone, the percentage value of Ni decreases drastically by 0.42%, while the percentage values of MgO and SiO$_2$ are relatively higher.

### 4.2.2. Type B Profile

Profile Type B represents a deposit covered by a relatively thick layer of clay and colluvium. Unlike the type A profile, this profile does not exhibit the presence of a limonite zone. The saprolite zone in the type B profile shows variations in the percentage of ultramafic rock fragments in the upper and lower parts. In the upper part, the saprolite layer contains a higher concentration of ultramafic rock fragments, thus referred to as rocky saprolite, while in the lower section, this layer includes a more significant proportion of ultramafic rock fragments compared to the rocky saprolite zone, and is referred to as saprolitic rock. Based on the results of XRF geochemical analysis (Fig. 8), the percentage of Ni grade in the clay and colluvium remains relatively stable, with a maximum value of 0.58%.

![Fig. 8. Borehole log of type B profile represented by hole ID DHPG17. Mineral abbreviations: GTH = goethite, HMT = hematite, MGH = maghemite, OL = olivine, PX = pyroxene, SER = serpentine, TLC = talc, SIL = silica.](image-url)
However, Fe, Al$_2$O$_3$, Co, MgO, and SiO$_2$ values exhibit less consistency as they enter the colluvium. As for the saprolite zone, the percentage of Ni grades shows no significant difference compared to the zone above, with a maximum of 0.57%. Conversely, the percentages of Fe, Al$_2$O$_3$, Co, and SiO$_2$ gradually increase in the saprolite and rocky saprolite zones but decrease in the saprolitic rock zone. On the other hand, the MgO values demonstrate a gradual decrease in both the saprolite and rocky saprolite zones but experience a notable increase in the saprolitic rock zone. As the analysis transitions into the bedrock zone, the percentage of Ni values remains consistent, while the percentages of Fe, Al$_2$O$_3$, Co, and SiO$_2$ once again decrease. Additionally, the percentage of MgO shows a gradual increase, reaching 36.5%.

4.2.3. Type C Profile

Type C profile is a deposit that is not covered by clay or colluvial deposits. This nickel deposit profile consists of topsoil (which is entirely composed of weathered rocks that have turned into residual soil), limonite, rocky saprolite, saprolitic rock, and bedrock. The topsoil in this profile has a thickness of 0.35 meters, brown in color, and consists of plant roots with no visible macroscopic mineral features. This topsoil layer is the result of the weathering of rocks that have transformed into residual soil, giving it a very fine texture. This is similar to the physical characteristics of limonite in other areas (Kusuma et al., 2019). Based on XRF geochemical analysis results (Fig. 9), the average percentage of Ni is 1.00%, Fe is 46.5%, Al$_2$O$_3$ is 8.90%, Co is 0.12%, MgO is 3.33%, and SiO$_2$ is 15.37%.

![Borehole log for type C profile represented by hole ID DHPG10. Mineral abbreviations: GTH = goethite, HMT = hematite, MGH = maghemite, OL = olivine, PX = pyroxene, SER = serpentine, TLC = talc, SIL = silica.](image)
The limonite zone has a thickness of 3.65 meters, with a brownish-yellow color and a fine texture due to extensive weathering, transforming the rock into residual soil characterized by high laterization. It consists predominantly of goethite and hematite minerals, as indicated by the percentage of Fe element, which is 45.99%. Based on XRF geochemical analysis, the percentages of Ni, Fe, Al₂O₃, Co, MgO, and SiO₂ elements are relatively consistent in the limonite zone. However, the high Fe, Al₂O₃, and Co values suggest that these elements are enriched in the limonite zone due to their low mobility (Ahmad, 2006). The saprolite zone has a thickness of 4.40 m, with a greenish-brown color. It consists of fine-textured to granular rocky saprolite where the original rock is still recognizable but extensively weathered. It is dominated by soft saprolite and coarse-textured rocky saprolite, where the original rock is clearly visible. The saprolite zone is composed of hematite, goethite, serpentine, pyroxene, and olivine minerals. According to XRF geochemical analysis, the percentage of Ni increases significantly in the rocky saprolite, reaching 2.91%, due to its accumulation and enrichment in this zone. The Ni percentage gradually decreases to 1.12% in the saprolitic rock zone. In the bedrock zone, the percentages of Ni, Fe, Al₂O₃, and Co elements gradually decrease while the percentage of MgO slowly increases. The percentage of SiO₂ element remains consistent, similar to the saprolite zone.

4.2.4. Type D Profile

Type D profile comprises clay, colluvium, and bedrock from top to bottom (Fig. 10) showing no laterite development in this deposit. It is believed that the limonite and saprolite have eroded and been transported elsewhere before the colluvium and clay deposition. The clay layer, with a thickness of 80 cm, consists of dark brown sediment material.

![Boreshole log for type D profile represented by hole ID DHPG15. Mineral abbreviations: OL = olivine, PX = pyroxene, SER = serpentine, SIL = silica.]

It exhibits good sorting and consists of very fine-grained particles that cannot be macroscopically identified. In the colluvium layer, pyroxene and olivine minerals can still be identified in their fragments.
Towards the lower part of this layer, these fragments undergo strong serpentinization, transforming into serpentinite. On the other hand, in the bedrock section, serpentine is dominantly present along with other minerals, such as olivine and pyroxene, albeit in lesser abundance. Additionally, quartz is also present in the bedrock as a vein-filling mineral. Based on the XRF geochemical analysis results when entering the clay and colluvium layers, the percentage values of Ni remain relatively consistent, ranging from 0.3% to 0.6%. Meanwhile, the percentage values of Fe, Al₂O₃, Co, and SiO₂ show a similar trend, where their concentrations decrease when entering the colluvium layer and increase when entering the bedrock layer. On the other hand, MgO exhibits a different trend. It tends to increase in the upper part of the colluvium layer and decrease in the lower part of the colluvium layer. Then, its percentage value rises again in the lower part of the bedrock zone.

4.3. The Potential of Lateritic Nickel in the Research Area

The determination of lateritic nickel deposit potential in the research area is based solely on the parameters of the average Ni grade (%) and the average thickness (m) of the laterite zone. Generally, the Ni content in laterite deposits has an average range of 1.0% to 2.5%, sometimes reaching 3.0%, depending on the factors influencing laterite formation in a particular area (Elias, 2002). In the research area, the grades and thicknesses vary for each zone. The highest average Ni grade is found in the saprolite zone, with progressively increasing grades from low to high in type B (0.8%), type C (1.77%), and type A (2.32%). In the limonite zone, the average Ni grade ranges from the lowest in type A at 1.21% to the highest in type C at 1.43%. Meanwhile, in the clay and colluvium layers, the average Ni grades are relatively lower compared to the two previous zones, with values of 0.42% (type A), 0.45% (type D), and 0.69% (type B) (Table 1). Based on the average Ni grades, especially in the saprolite zone, type A and type C profiles are two profile types in the research area with the potential for further development.

Table 1. The average thickness and Ni grades in the clay and colluvium, limonite, and saprolite zones for each profile type

<table>
<thead>
<tr>
<th>Profile Types</th>
<th>Clay + Colluvium Thickness (m)</th>
<th>Ni (%)</th>
<th>Limonite Thickness (m)</th>
<th>Ni (%)</th>
<th>Saprolite Thickness (m)</th>
<th>Ni (%)</th>
<th>Bedrock Thickness (m)</th>
<th>Ni (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>11.03</td>
<td>0.42</td>
<td>3.46</td>
<td>1.21</td>
<td>5.35</td>
<td>2.32</td>
<td>UK</td>
<td>0.58</td>
</tr>
<tr>
<td>Type B</td>
<td>12.71</td>
<td>0.69</td>
<td>NF</td>
<td>NF</td>
<td>3.61</td>
<td>0.80</td>
<td>UK</td>
<td>0.35</td>
</tr>
<tr>
<td>Type C</td>
<td>NF</td>
<td>NF</td>
<td>5.13</td>
<td>1.43</td>
<td>7.51</td>
<td>1.77</td>
<td>UK</td>
<td>0.50</td>
</tr>
<tr>
<td>Type D</td>
<td>12.91</td>
<td>0.45</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>UK</td>
<td>0.55</td>
</tr>
</tbody>
</table>

NF: Non-Found, UK: Unknown

Furthermore, the average Ni grades of each zone in the type A profile and type C are compared with their respective thicknesses (Fig. 9). In the type A profile, there is a good enrichment of Ni (0.42% Ni) despite being covered by clay and colluvium with a thickness of 11.03 m. The average thickness of the limonite zone in this profile type is 3.46 meters, with an average Ni grade of 1.21%. Meanwhile, the average thickness of the saprolite zone in the type A profile is 5.35 meters, with an average Ni grade of 2.32% (Table 1; Fig. 9). In contrast, to the type A, the type C profile does not show the presence of clay and colluvium (Fig. 6). The uppermost zone in this type is the topsoil, which is a reddish-brown residual soil rich in iron oxides with an average thickness of 0.71 meters and an average Ni grade of 1.24%. Below the topsoil, the limonite zone has an average thickness of 5.13 m with an average Ni grade of 1.43%. Furthermore, the saprolite zone has an average thickness of 7.51 m with an average Ni grade of
1.77% (Fig. 11). The significant Ni enrichment and the presence of a relatively thick saprolite zone indicate that both type A and type C profiles have good potential to develop.

Fig. 11. A graph comparing the average thickness and Ni grade from (a) type A profile and (b) type C profile.

As mentioned, deposits with good nickel potential are found in types A and C profiles due to their high nickel grades and thick saprolite zones. It is worth noting that a nickel grade of 1.6% is currently considered suitable for processing by nickel smelters in Indonesia. The presence of clay and colluvium in the type A profile is unique. Typically, laterite profiles covered by clay indicate poor laterization development due to restricted groundwater movement (Golightly, 1981). However, despite being covered by clay, the type A profile shows the opposite trend in the research area. Laterization has developed well in this profile, with a significantly high average nickel content in the saprolite, reaching 2.32%. Based on observations of drilling data (core samples) and 2D cross-sectional visualizations shown in Fig. 6, there are two possible explanations for the high nickel content in the clay-covered profile. First, the clay covering type A profile is transported material that was deposited after laterization had already occurred in the parent rock. This is supported by unconsolidated ultramafic rock fragments ranging from gravel to cobbles within the colluvium beneath the clay layer. Second, the high nickel content in type A profile is influenced by topography. Referring to the 2D cross-section (Fig. 6), the borehole locations of the type A profile are situated on lower-elevation slopes than those of type C. Nickel, being a more mobile element, follows groundwater flow towards areas with lower water table elevations (Golightly, 1981; Elias, 2002; Ilyas and Koike, 2012; Ilyas et al., 2016; Irfan et al., 2021).

5. Conclusions

This study has produced the following findings, which are based on the results and discussions presented:

- The bedrock underlying the research area consists of two units: serpentinized lherzolite and serpentinite.
- The laterite profiles in the research area are categorized into four types: type A (composed from bottom to top of bedrock, saprolite, and limonite, all of which are covered by clay and colluvium), type B (characterized by the absence of limonite in the profile, the presence of saprolitic rock and rocky saprolite above the bedrock), type C (composed of layers of bedrock, saprolitic rock, rocky saprolite, limonite, and topsoil), and type D profile (consisting of three zones, namely bedrock, colluvium, and clay, and lacking limonite and saprolite layers).
- Among the four recognized profile types, types A and C profiles have good potential compared to types B and D because of their high average nickel content and thick saprolite zones.
Acknowledgements

The author would like to thank Mr. Ishak Syafei for providing access to the exploration data. The field data collection would not have been successful without the assistance and guidance from Mr. Diyan Hermawa S.T. Therefore, the author extends their heartfelt thanks. Additionally, the author would like to express deep gratitude to the reviewers for providing valuable suggestions that significantly contributed to the writing of this paper.

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