http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 10 No 04-2/2025

RESEARCH ARTICLE

Geochemical Properties and Critical Elements Potential of Ni-Laterite Deposits in Advancing Clean Energy Technology Development

Dian Yesy Fatimah[1,*], Erwin Setiawan[2], Adhen Salahudin Al Ayubi Prasojo[1], Febria Ulvah[1], Rizki Kurniawan[1]

[1] Department of Geological Engineering, Faculty of Exploration and Production Technology, Universitas Pertamina, Jakarta.
[2] Pomalaa Nickel Laterite Exploration Team PT Antam Tbk Unit Geomin, Pomalaa, Southeast Sulawesi.

* Corresponding author : dian.fatimah@universitaspertamina.ac.id
Tel.:+62 81-23-431-9289

Received: Jul 22, 2025; Accepted: Jan 9, 2025.
DOI: 10.25299/jgeet.2025.10.1.1.24150

Abstract

Critical elements refer to a group of elements that possess strategic significance and play a vital role in the national economy, as well as in national defense and security. These minerals are at risk of supply disruptions and lack suitable substitutes. In clean energy industries, critical elements are particularly important, especially for electric vehicle components. Aligned with national commitments expressed in the G20 Leaders' Declaration. Nickel laterite deposits are one of the key sources with high potential for critical elements. This research focuses on critical elements in nickel deposits, which are Ni, Co, Mn, Cr and Al, and their resource potential in Kolaka, Southeast Sulawesi. The methods used are geochemical data, field data, and reference studies. The methods used in the research include literature study, X-Ray Fluorescence (XRF) geochemical analysis of all samples using the Exploratory Data Analysis (EDA) method using Microsoft Excel, Data modelling using scatter plot and heatmap of spearman correlation. The findings indicate that the enrichment of critical elements such as cobalt (Co), manganese (Mn), aluminum (Al), and chromium (Cr) is concentrated in the limonite zone and associated with Fe with various ranges of 0.04-0.14% Co, 0.27-1.13% MnO, 1.03-4.60%Cr_2O_3, 2.82-9.94% Al_2O_3 content, whereas nickel (Ni) is enriched in the saprolite zone and associated with Mg with a various range 0.5-3.17%Ni. Overall, the concentration of critical elements other than Ni and Co is typically lower in nickel laterite deposits with high nickel content. With continuous advancements in extraction technologies through research, all zones of laterization in nickel laterite deposits, not just the nickel-rich saprolite zone, could be optimally utilized. This would enhance the potential of nickel laterite deposits as a valuable commodity, contributing significantly to the acceleration of the energy transition towards cleaner energy through clean energy-based technologies.

Keywords: *Critical elements, Ni-Laterite, Clean Energy, Geochemical*

---

1. Introduction

Critical elements are minerals that have strategic prospects and have an important role in the national economy and national defense and security which have the potential for supply disruption and there is no suitable substitute for these elements (Kementerian Energi dan Sumber Daya Mineral, 2023). In clean energy-based industries, critical elements play an important role in various aspects, especially in electric vehicle components. In line with the national commitment declared in the G20 Leaders' Declaration, Indonesia is committed to reducing carbon emissions and the use of coal energy as well as encouraging the use of cleaner energy to support sustainable development. Therefore, the value of critical elements has increased significantly.

One of the mineral deposits that has large critical elements potential is nickel laterite deposits. Nickel laterite is the remaining product of chemical weathering of ultramafic rocks that occurs on the earth's surface. This weathering occurs because some primary minerals become unstable in the presence of water. These primary minerals will decompose and form new, more stable minerals. Laterite is very important as a source of ore deposits because in certain cases this process is very efficient in forming certain elements such as Mg, Fe, Si, Cr, Al, Mn and Co. One of the important elements produced by the laterization process is nickel (Elias, 2002). Nickel laterite is the result of laterization of ultramafic rocks which have a primary Ni content of 0.2 – 0.4% (Golightly, 1981 in Elias, 2002). In general, laterization zones in laterite nickel deposits can be classified into ferricrete, limonite, saprolite, saprock, and bedrock. Each zone has its own characteristics. The ferricrete and limonite zones are oxidation zones, so minerals carrying oxide elements such as hematite (Fe_2O_3), goethite ($FeO(OH)$), manganite ($MnO(OH)$), maghemite (Fe_2O_3), chromite ($FeCr_2O_4$), and gibbsite ($Al(OH)_3$) are commonly found. Meanwhile, the saprolite zone is a reduction zone, so minerals such as serpentine ($Mg_3Si_2O_5(OH)_4$), chlorite ($(Mg)_6(Si)_4O_{10}(OH)_9$), and talc ($Mg_3Si_4O_{10}(OH)_2$) tend to be found there. Saprock and bedrock are characterized by a low degree of weathering, so primary minerals tend to still be present. Generally, ultramafic rocks that produce nickel laterite are dunite, harzburgite and peridotite which are in the ophiolite complex. The process and characteristics of laterization are controlled by local and regional effects, such as climate, topography, tectonics, bedrock, and structure.

Indonesia is the largest nickel producing region in the world with total reserves reaching 5 billion tons and nickel production in 2023 reaching 175 million tons (Kementerian Energi dan Sumber Daya Mineral, 2024). One of the areas with the largest nickel reserves is Southeast Sulawesi Province. Therefore, a study was conducted to explain the correlation of critical elements with the main elements of nickel laterite deposits, the occurrence of critical elements, and the potential of critical elements in nickel laterite deposits to support the development of clean energy-based technology.

Critical elements are important commodities in the national economy and national defense and security and have the potential for supply disruption due to their limited quantity and lack of suitable substitutes (Kementerian Energi dan Sumber Daya Mineral, 2023). Apart from that, critical elements have a strategic role in the energy transition towards cleaner and lower carbon energy. Indonesia, which is one of the countries that has committed to using cleaner energy, has quite a big advantage with the presence of critical elements which are quite abundant and diverse in Indonesia, especially critical elements which are the main commodity in the energy transition towards cleaner energy. One sector that has quite large potential is the battery industry (Agnia et al., 2024). The battery industry sector has an important role in supporting other industries such as new renewable industries, transportation, and technology-based industries (Khairunnisa, 2025).

Some critical elements that are important commodities in the battery industry are copper, aluminum, phosphorus, iron, manganese, graphite, nickel, cobalt, and lithium (Gielen, 2021). These critical elements have a strategic role in the development of the battery industry which supports other industries. Seeing the increasing trend in the development of battery-based industries in line with national and international commitments in transitioning to cleaner energy use, it is estimated that critical elements will experience an increase in demand until 2030. **Fig. 1** shows the important role of copper, aluminum and graphite as mixed materials in batteries and lithium, cobalt, and nickel are the main materials that establish up to 50% of the composition of batteries (Gielen, 2021).

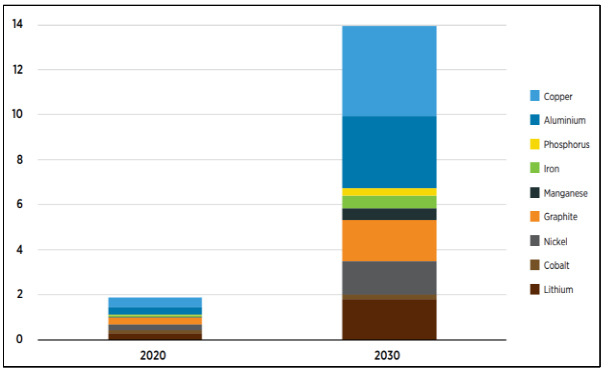


Fig 1. Projected demand for critical elements in the battery industry until 2030 reaches 14 million tons. This projection is based on international commitments to transition to cleaner energy use (Gielen, 2021).

3. Geological Setting

Based on stratigraphy-tectonics, Sulawesi Island, which has a distinctive shape resembling the letter "K", is divided into 3 lithotectonics, namely the West Sulawesi Volcano-Plutonic Arc, the Central Sulawesi Metamorphic Belt, and the ophiolite rock complex known as the East Sulawesi Ophiolite (OST) (**Fig. 2**) (Kadarusman et al., 2004).

The West Sulawesi Volcano-Plutonic Arc is pre-Cretaceous accretionary material in the western part of Sulawesi which later developed into the Neogene volcanic arc; The volcanic arc consists of a mid-Mesozoic bedrock complex, a Late Cretaceous-Middle Eocene volcanic arc, a non-volcanic sequence of Upper Eocene - Lower Miocene carbonate rocks and a Miocene - Quaternary volcanic arc. The volcanic Neogene phase is spread across the western part of Sulawesi. The Central Sulawesi Metamorphic Belt is a metamorphic rock belt that developed in central Sulawesi and the southeast arm. The metamorphic belt consists of a collection of greenschist and blueschist metamorphic facies, with blueschist increasing in abundance towards the west. The western edge of this belt is where a collection of high-pressure rocks is separated from high-temperature schist, gneiss, and granitic rocks. The East Sulawesi Ophiolite (OST) develops in the eastern arm and continues to the southeastern arm of Sulawesi. The complex is dominated by large-bodied ophiolites that have been disturbed and experienced tectonic events. OST is separated geographically into northern and southern segments. The northern segment appears on the eastern arm of Sulawesi and contains quite complete ophiolite even though it has experienced tectonic events. In the southern segment, it is only found at fault contacts with crystalline rocks consisting mainly of harzburgite and serpentinized harzburgite.

In general, the development of the geological structure of East Sulawesi can be divided into 2 parts, namely the northern and southern parts of East Sulawesi. In the

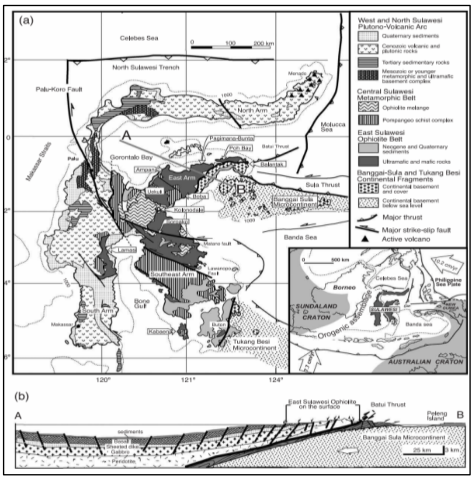


Fig 2. Lithotectonics of Sulawesi Island (Kadarusman et al., 2004)

northern part of East Sulawesi there is the Sorong Fault System which is a left-lateral transform fault. This fault then broke down into the South Sula Fault and North Sula Fault in the Sula Islands and Banggai Islands. The ends of these two faults form the Batui Fault which is a thrust fault. There are also imbricated structures from thrust faults resulting from the collision of the Banggai-Sula microcontinent with eastern Sulawesi in the Late Miocene.

This imbricated structure continues to the southern part of East Sulawesi. Apart from that, in this region there are also folds caused by the Late Miocene collision. In the post-collision period, the Metarombeo Fault was formed in the form of a left-lateral strike slip fault and the Lawanopo Fault System which was oriented northwest-southeast. Apart from that, the Konaweha Fault and Kolaka Fault were also formed. The Konaweha Fault stretches for 50 km and cuts through the rocks along the Konaweha River. Meanwhile, the Kolaka Fault stretches for 250 km, starting from the west coast of Bone Bay to the southern tip of the Southeast Arm of Sulawesi (Zakaria and Sidarto, 2015).

3. Material and Method

In this research, the data used is exploration data from 11 drilled wells carried out in the PT ANTAM Tbk exploration area in Pomalaa, Kolaka, Southeast Sulawesi using a YBM single tube drilling machine. The samples from the 11 drill points have a diameter of 6cm with varying sample lengths for each drill with the shortest being 8m and the longest being 44m. Drilling was carried out until it penetrated the bedrock to a depth of 3m.

The drilling samples were then prepared in the preparation laboratory by drying the samples at a temperature of 110°C for approximately 17 hours. The dried samples were then crushed using a jaw crusher and pulverizer to obtain samples measuring approximately 200 mesh. Samples that are 200 mesh in size are then packed in sample plastic weighing 200 grams. After all samples have been prepared, geochemical analysis is then carried out using the XRF method to obtain the percentage of elements in each depth sample.

The results of the geochemical analysis of all samples were then analyzed again using the Exploratory Data Analysis (EDA) method using the Excel to group the data based on FeO, SiO_2 and MgO content values so that data groups were obtained in the form of topsoil (TP), limonite (L), saprolite (S), bedrock (BR), boulder (BD) and high silica (HS). After the data grouping was completed, an analysis of the groups was then carried out by making a correlation between Fe SiO_2 and Mg with all the critical elements found in the nickel laterite deposits to determine each profile of nickel laterite deposits, correlation of Fe and Mg as major elements of limonite and saprolite zone with other critical elements such as Co, Mn, Al, Cr and Ni to determine the correlation between them, spearman correlation all of elements to determine the correlation each other and a geochemical profile of nickel laterite was created to determine the distribution of critical elements.

4. Result and Discussion

The determination of laterization zones in nickel laterite deposits is carried out using geochemical data. Geochemical data plays an important role because the unique characteristics of each zone and the high concentration of certain elements serve as indicators in dividing these zones. The division of the laterization zones can be seen using the SiO_2, MgO and FeO ternary diagram as in **Fig. 3**. In this figure the division of laterization zones starting from topsoil, limonite, saprolite, boulder, high silica, and bedrock (Handika et al., 2024). The topsoil and limonite zones are characterized by the presence of high Fe and the MgO (Hasria et al., 2024) which tends to be low, then the saprolite zone is characterized by a percentage of MgO that is not too high, ranging below 40 percent, in contrast to bedrock and boulders which tend to have a higher percentage of MgO, while the zone with high levels High silica is called the high silica zone.

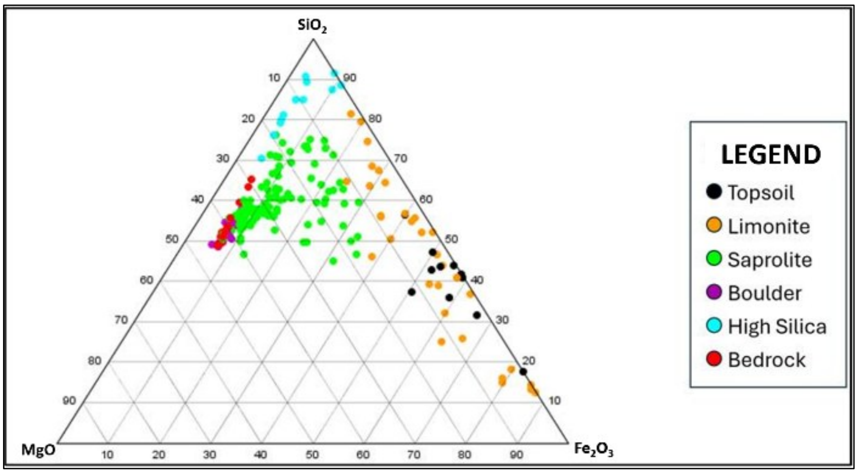
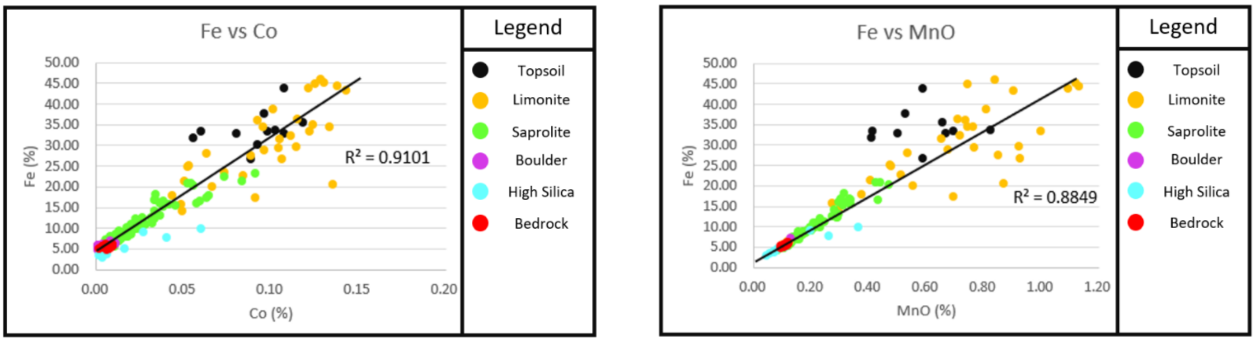


Fig 3. Division of laterization zones using a ternary diagram which divides laterization zones into topsoil, limonite, saprolite, boulder, high silica and bedrock based on the percentage of SiO_2, MgO and Fe_2O_3 elements.

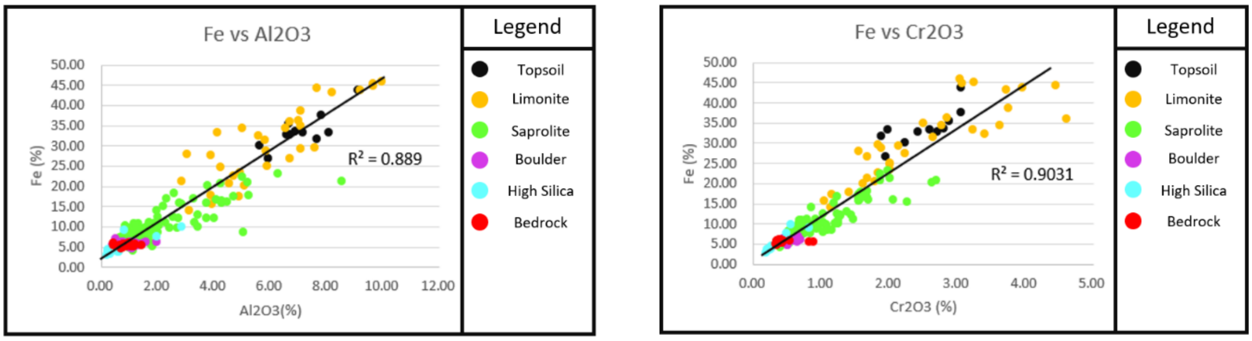
Understanding the enrichment of critical elements in nickel laterite deposits, knowing their correlation characteristics with the main elements of nickel laterite deposits will be the main key in understanding the enrichment processes and zones. In nickel laterite deposits there are several element characteristics based on their mobility, there are mobile, semi-mobile and immobile elements (Langkoke et al., 2024). Elemental mobility is the main key to why critical elements can experience enrichment in the limonite and saprolite zones (Bargawa et al., 2021). When weathering occurs on ultramafic rocks (dunite, harzburgite and peridotite), elements that have very low mobility tend to remain in the upper layer of the laterite profile such as Fe, Co, Mn, Cr and Al, while elements that have high mobility such as Ni and Mg tend to join with water (Irzon, 2017). The soil descends to the bottom of the laterite profile.

The scatter plot of Fe elements with other critical elements especially Co, Mn, Cr and Al show strong positive correlation. **Fig. 4**, this indicates that Fe and these elements have a very good correlation, thus indicating that critical elements will accumulate well in zones with high Fe content. The accumulation of critical elements in the limonite zone is also inseparable from the role of oxidation-reduction reactions (Ito et al., 2021; Aquino et al., 2022). The limonite zone is located above the groundwater level which causes the oxidation process to occur (Fitri, 2023). This oxidation process causes Co, Mn, Cr and Al to become saturated and accumulate in the oxidation zone or limonite zone (Irzon, 2017).



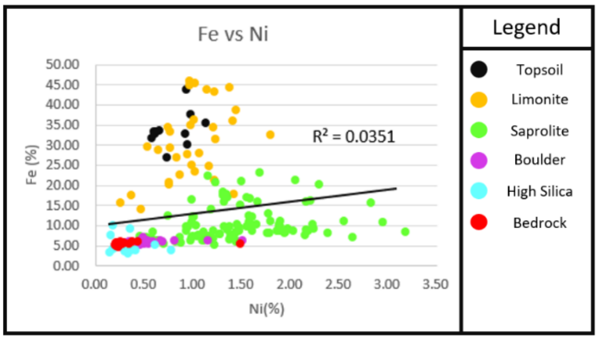
Correlation of Fe and Co in each laterization zone of nickel laterite deposits.

Correlation of Fe and Mn in each laterization zone of nickel laterite deposits.



Correlation of Fe and Al in each laterization zone of nickel laterite deposits.

Correlation of Fe and Cr in each laterization zone of nickel laterite deposits.

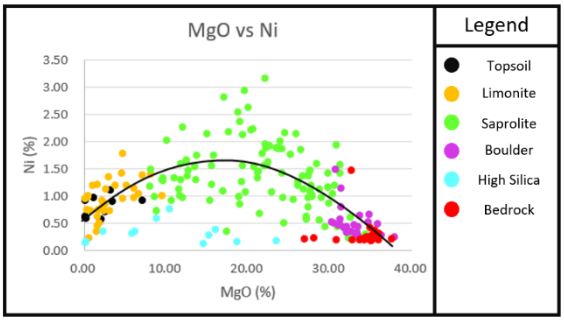


Correlation of Fe and Ni in each laterization zone of nickel laterite deposits.

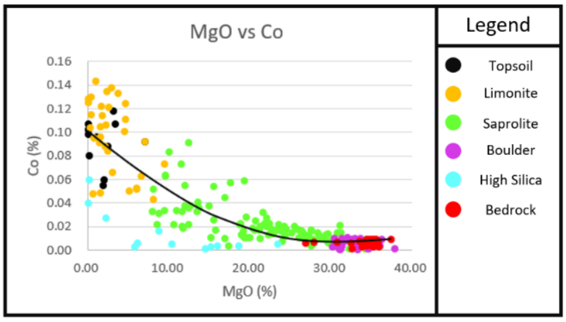
Fig 4. Correlation of Fe and Co, Mn, Al, Cr, and Ni in each laterization zone of nickel laterite deposits.

Fig. 5 shows a comparison of the correlation between Mg as a characteristic of the saprolite zone and other critical elements in nickel laterite deposits. In the graph, it is observed that Mg has a negative correlation with Co, Mn, Cr and Al, which means that Mg has no correlation with these critical elements. This is related to the nature of these critical elements, Co, Mn, Cr and Al tend to accumulate in the limonite zone or oxidation zone, while Mg, which is a mobile element, tends to accumulate in the saprolite zone. Thus, it is quite difficult to find Co, Mn, Cr and Al in the saprolite zone. Meanwhile, the relationship between Mg and Ni shows a quite unique correlation. The correlation between Mg and Ni shows a curvilinear correlation, this indicates that initially the two elements had a positive correlation, indicating an increase in Mg levels in line with Ni, but when it reached a certain point, the correlation changed to negative, indicating that the increase in Mg levels began to be inconsistent with Ni.

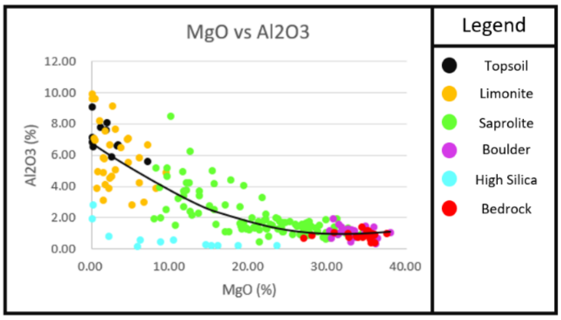
This unique relationship between Ni and Mg also illustrates how the nickel enrichment process occurs as in **Fig. 6.** The nickel enrichment process starts with the weathering of ultramafic rocks (Qi et al., 2024). During the weathering process, immobile elements will remain in the upper part of the laterization zone, causing these elements to precipitate and form minerals (Choi et al., 2021), one of which is the goethite mineral, which is formed in the lower limonite zone, while the mobile elements will transport into the lower laterite profile, this is illustrated in Fig. 14 on the leaching zone. Furthermore, when these mobile elements are carried by water to the bottom of the laterite profile, Ni is adsorbed by goethite minerals which causes nickel enrichment to occur in the limonite zone (Domènech et al., 2020; Astuti et al., 2024). This is the reason why in several cases nickel enrichment was found to occur in the limonite zone. Furthermore, when the weathering process continues and vegetation begins to grow in the laterization area, the



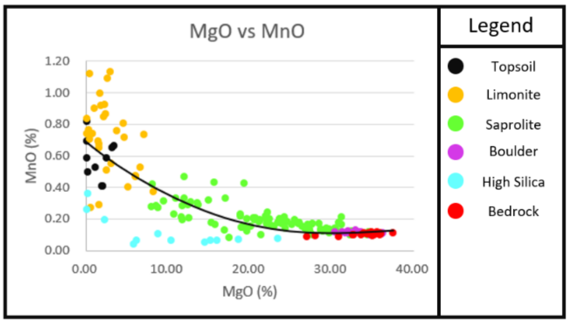
Correlation of Mg and Ni in each laterization zone of nickel laterite deposits



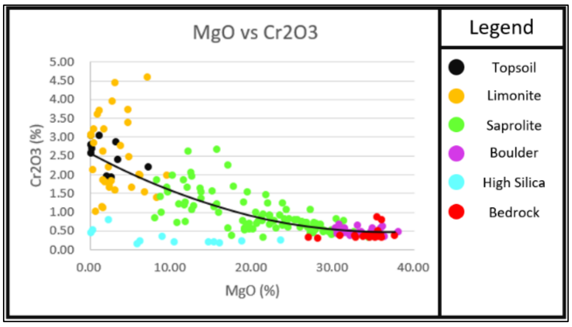
Correlation of Mg and Co in each laterization zone of nickel laterite deposits



Correlation of Mg and Al in each laterization zone of nickel laterite deposits



Correlation of Mg and Mn in each laterization zone of nickel laterite deposits



Correlation of Mg and Cr in each laterization zone of nickel laterite deposits

Fig 5. Correlation of Mg and Ni, Co, Al, Mn, and Cr in each laterization zone of nickel laterite deposits.

meteoric water will react with the remains of dead plants causing the water to become more acidic. This acidic water causes the Ni that was initially adsorbed by goethite, to be released (Ma et al., 2015). Ni, which becomes a free element, is carried back by water to the bottom of the laterite profile and is again adsorbed by existing goethite or serpentine minerals (Fan and Gerson, 2015). When Ni meets serpentine, Ni will be adsorbed by the serpentine, and the Mg element will be released from the serpentine. This process is called the process of element substitution and nickel enrichment (Ahmad, 2008; Freyssinet et al., 2005). Mg will dissolve in ground water because it is more stable in ground water. The nickel enrichment process is depicted in **Fig. 6** in the enrichment zone. Mg-rich zone is a zone where there has been no substitution between Ni and Mg.

In **Fig. 7** it can also be seen that Co, Mn, Cr and Al not only have a good correlation with Fe but with each other with these minerals. In Fig. 15 show that the critical elements which are included in the oxide elements such as Co, Mn, Cr and Al have a very strong correlation with each other, this happen because the enrichment of these critical elements occurs in the same zone, namely the limonite zone and the oxidation process. which is the main factor in the enrichment of these critical elements in the limonite zone. By knowing the correlation between critical elements, it can make it easier to identify critical elements enrichment zones and make the exploration and production process easier by knowing the location of critical elements enrichment.

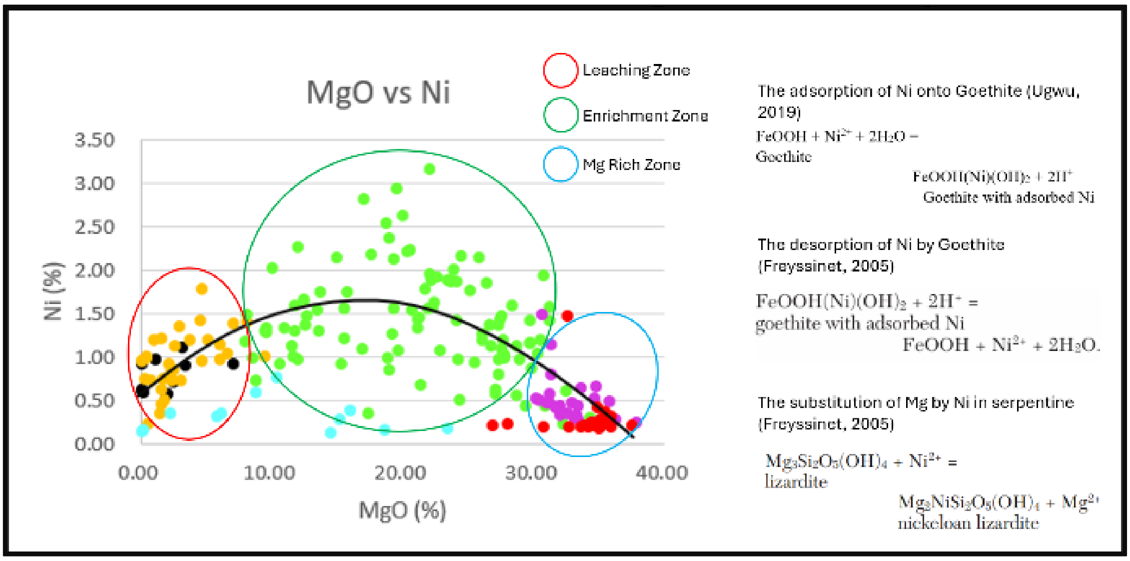
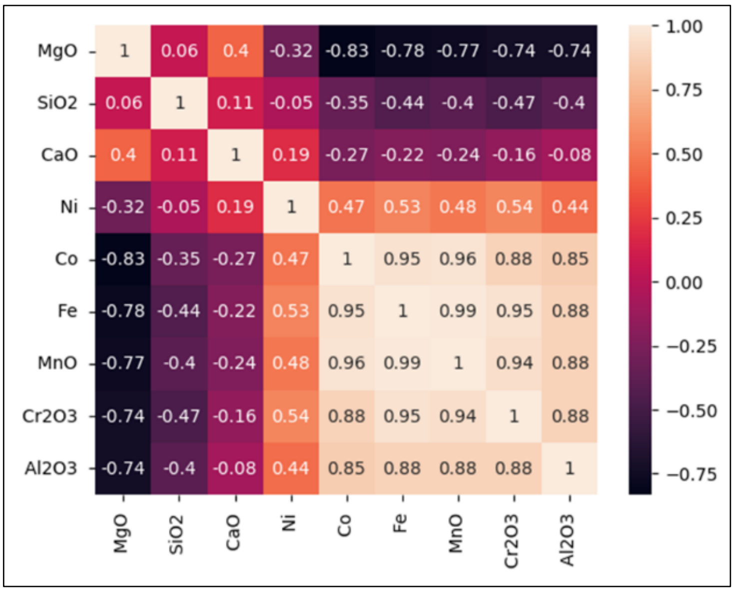


Fig 6. Comparison graph between Mg and Ni depicting the leaching process in the topsoil and limonite zones, enrichment in the saprolite zone and zones that have not experienced weathering



	MgO	SiO2	CaO	Ni	Co	Fe	MnO	Cr2O3	Al2O3
MgO	1	0.06	0.4	-0.32	-0.83	-0.78	-0.77	-0.74	-0.74
SiO2	0.06	1	0.11	-0.05	-0.35	-0.44	-0.4	-0.47	-0.4
CaO	0.4	0.11	1	0.19	-0.27	-0.22	-0.24	-0.16	-0.08
Ni	-0.32	-0.05	0.19	1	0.47	0.53	0.48	0.54	0.44
Co	-0.83	-0.35	-0.27	0.47	1	0.95	0.96	0.88	0.85
Fe	-0.78	-0.44	-0.22	0.53	0.95	1	0.99	0.95	0.88
MnO	-0.77	-0.4	-0.24	0.48	0.96	0.99	1	0.94	0.88
Cr2O3	-0.74	-0.47	-0.16	0.54	0.88	0.95	0.94	1	0.88
Al2O3	-0.74	-0.4	-0.08	0.44	0.85	0.88	0.88	0.88	1

Fig 7. Heatmap of spearman correlation matrix between all elements in nickel laterite deposits with a value of 1 which means it has a very strong correlation, 0 which means it is neutral and -1 which means it is not correlated.

Geochemical profile shows a graph of the percentage of elements in nickel laterite deposits can be seen based on depth intervals as in Fig. 16 and Fig. 17 which are the laterite geochemical profiles from wells TB08 and TB09. In **Fig. 8** and **Fig. 9** it is observed that the limonite and saprolite zones are locations for the enrichment of several critical elements and minerals. It was observed that in the limonite zone, oxide elements such as Fe, Co, Mn, Cr and Al experienced significant enrichment, while in the saprolite zone the elements Mg and Ni were enriched. The findings indicate that the enrichment of critical elements such as Co, Mn, Al, and Cr is concentrated in the limonite zone with various ranges of 0.04-0.14% Co, 0.27-1.13% MnO, 1,03-4,60% Cr_2O_3, 2.82-9.94% Al_2O_3 content, whereas Ni is enriched in the saprolite zone with a various range 0.5-3.17%Ni.

Critical elements in the battery industry found in nickel laterite deposits include Ni, Co, Mn, and Al (Eljoudiani et al., 2025). The potential for these critical elements in nickel laterite deposits is quite well seen in the geochemical profile of nickel laterite in the previous discussion. Utilization of the laterization zone of nickel laterite deposits has not yet been carried out optimally, focusing on the saprolite zone, even though the limonite zone also has potential, especially in critical elements. Critical elements that can be found in the limonite zone are Co, Mn, and Al (Haya et al., 2019). However, there is a quite important problem in the critical elements' potential of nickel laterite deposits, the percentage of critical elements content which is quite low when compared to the main commodity, Ni. A low-grade percentage means that the smelting process cannot be carried out considering that refining technology is not yet capable of further processing critical elements with low grades (Zhang et al., 2021; Mudd & Jowitt, 2018). This relatively low-grade percentage poses a new challenge in further processing critical elements in nickel laterite deposits. On the other hand, exploitation of critical elements which can coincide with nickel production can reduce production costs. Thus, low grade critical elements purification technology needs to be further developed for maximum utilization of critical elements in nickel laterite deposits (Zhang et al., 2025; Mamyrbayeva et al., 2024).

The low percentage of critical elements found in nickel laterite deposits is indeed a challenge for the government in processing this material further, but extraction in conjunction with the production of the main product, Ni, can reduce costs (Zhang et al., 2025). Apart from that, further utilization of critical elements in nickel laterite

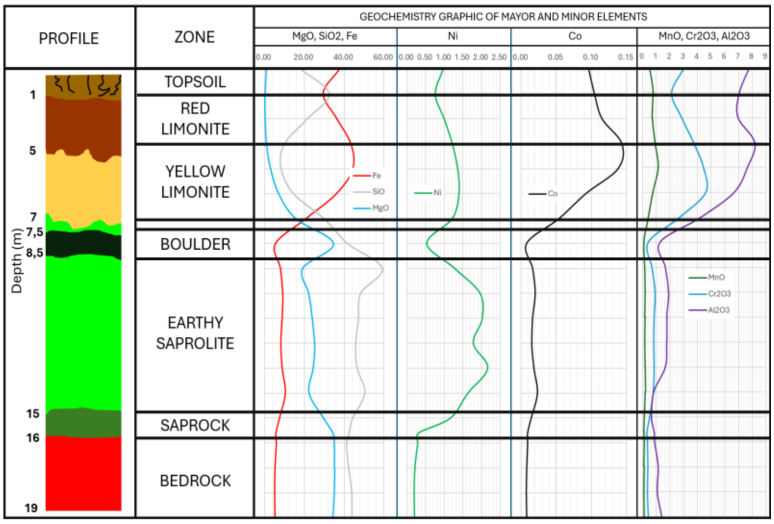


Fig 8. Geochemical profile of TB08 showing the percentage of elements at 1 meter depth intervals

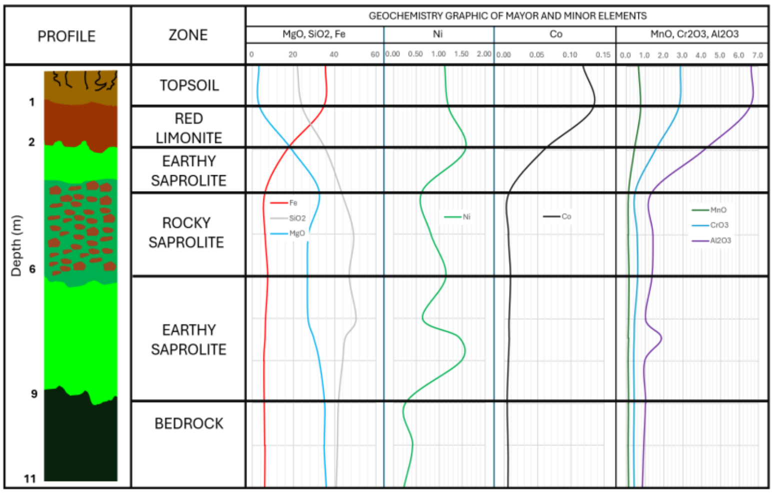


Fig 9. Geochemical profile of TB09 showing the percentage of elements at 1 meter depth intervals

deposits can bring huge profits to the government considering the huge potential of these critical elements in various sectors, not only in the battery industry sector. In wind turbine technology Cr, Mn and Ni take a key role along with other critical elements as well as in nuclear-based technology facilities, aluminum takes a key role in the electricity distribution industry (EITI, 2022). Thus, maximizing utilization of all existing potential, both small and large, will have big implications in the future. Utilizing every potential that exists from critical elements, both in ore deposits and nickel laterite deposits, has enormous benefits for the community, government, and related companies as long as utilization can be carried out optimally without problems such as poor management, corruption and socio-environmental problems. The benefits obtained from the use of critical elements for society can be that access to clean energy technology becomes easier and cheaper so that people of all groups can experience this technology and can take a role in the transition to cleaner energy. Currently, clean energy-based technology is quite difficult to access and has a high enough value so that not all levels of society can benefit from it (Ockwell et al., 2021). For the government and companies, the maximum use of critical elements in nickel laterite deposits can bring benefits because the extracted material can be utilized optimally, no longer focused only on one of the laterization zones, the saprolite zone, but on the limonite zone, which is currently still a residual material can be utilized further.

The potential for critical elements is very broad in various fields, especially the clean energy-based technology industrial sector, a low percentage of grade should no longer be a major problem in exploiting any existing potential. Further innovation and research related to refining technology needs to be developed so that every potential that exists in critical elements bodies, both in small and large quantities, can be utilized optimally and the government can fulfill its commitment in supporting the energy transition towards cleaner energy.

5. Conclusion

The presence of critical elements in laterite nickel deposits is closely related to the occurrence of certain elements in laterite nickel deposits. In the limonite zone, Fe has a very strong correlation with Co, Mn, Cr, and Al, indicating that the enrichment of these elements occurs in zones rich in Fe, namely the limonite zone. The enrichment that occurs in the limonite zone is inseparable from the characteristics of the zone, which is an oxidation zone. When the oxidation process occurs, mobile elements will tend to dissolve and be carried to deeper profiles, while non-mobile elements will remain in the limonite zone, causing the percentage of Fe, Co, Mn, Cr, and Al to increase and then decrease with increasing depth. Thus, exploration and exploitation to utilize these elements can be carried out in the limonite zone. The saprolite zone, which is a reduction zone, is the main location for the accumulation of mobile elements such as Mg, Si, and Ni, so that the critical element Ni will be very high in the saprolite zone. Thus, exploration and exploitation to utilize Ni can be carried out in the saprolite zone. The saprock and bedrock zones, which are zones with a low degree of weathering, do not cause the accumulation of critical elements, so these zones are not the main targets in the exploration and exploitation of critical elements.

Critical elements in nickel laterite deposits are based on the Decree of the Minister of Energy and Mineral Resources regarding the determination of types of commodities that fall into the critical elements classification including Mg, Ni, Co, Mn, Cr and Al. The potential for these critical elements in nickel laterite deposits is quite good even though the levels are relatively low when compared to the main commodity, the limonite zone which has the potential for critical elements with various ranges of 0.04-0.14 % Co, 0.27-1.13 % MnO, 1,03-4,60 % Cr_2O_3, 2.82-9.94 % Al_2O_3 content, whereas Ni is enriched in the saprolite zone with a various range 0.5-3.17 % Ni. With the development of refining technology and innovation in the utilization of native minerals in nickel laterite deposits, critical elements in nickel laterite deposits can play a role in meeting market needs to support the development of clean energy-based technology.

Acknowledgements

We are thankful to Mr. Erwin Setiawan and Nickel Laterite Exploration Team PT Antam Tbk Unit Geomin for permission in the collection of the field as well as geochemical data.

References

Agnia, D., Nainggolan, D. F., Hardiwiyana, L., Riskikasari, P., & Hutabarat, Y. A., 2024. Keunggulan Komparatif Nikel Indonesia terhadap Kebutuhan Baterai Mobil Listrik di Pasar ASEAN. Musytari: Jurnal Manajemen, Akuntansi, dan Ekonomi, 10(12), 51–60. https://doi.org/10.8734/musytari.v10i12.7610

Ahmad, W., 2008. Nickel Laterites Fundamentals of chemistry, mineralogy, weathering processes, formation, and exploration. Indonesia.

Astuti, W., Avista, D., Prihutami, P., Wanta, K. C., Prakosa, A., Anggara, F., & Petrus, H. T. B. M., 2024. Atmospheric Leaching Behavior and Kinetics of Nickel and Cobalt from Halmahera Limonite Ore. International Journal of Technology, 15(4), 824-833. https://doi.org/10.14716/ijtech.v15i4.5607

Aquino, K. A., Arcilla, C. A., Schardt, C., & Tupaz, C. A. J., 2022. Mineralogical and geochemical characterization of the Sta. Cruz nickel laterite deposit, Zambales, Philippines. Minerals, 12(3), 305. https://doi.org/10.3390/min12030305

Bargawa, W. S., Hariyanto, R., Lusantono, O. W., Bramida, R. F., & Nugroho, S. P., 2021. Nickel laterite resources modeling using geological domain algorithm. GEOMATE Journal, 20(77), 189-196. https://doi.org/10.21660/2020.77.j2011

Choi, Y., Lee, I., & Moon, I., 2021. Geochemical and mineralogical characteristics of garnierite from the Morowali Ni-Laterite deposit in Sulawesi, Indonesia. Frontiers in Earth Science, 9, 761748. https://doi.org/10.3389/feart.2021.761748

Domènech, C., Galí, S., Soler, J. M., 2020. The Loma de Hierro Ni-laterite deposit (Venezuela): Mineralogical and chemical composition. Boletín de la Sociedad Geológica Mexicana, 72(3). https://doi.org/10.7440/res64.2018.03

EITI, 2022. Making the grade: Strengthening governance of critical elements POLICY BRIEF Strengthening governance of critical elements. Norway.

Elias, M., 2002. Nickel laterite deposits-geological overview, resources and exploitation. CODES Centre for Ore Deposit Research Special Publication 4 205–220.

Eljoudiani, A., Medeiros Veras, M., Sampaio, C. H., Moncunill, J. O., Tampouris, S., & Cortina Pallas, J. L., 2025. The

Concentration of Nickel and Cobalt from Agios Ioannis Laterites by Multi-Gravity Separator. Minerals, 15(7), 714. https://doi.org/10.3390/min15070714

Fan, R., & Gerson, A. R., 2015. Synchrotron micro-spectroscopic examination of Indonesian nickel laterites. American Mineralogist, 100(4), 926-934. https://doi.org/10.2138/am-2015-5093

Fitri, A., 2023. Comparative Analysis of water content in laterite nickel in the limonite an saprolite zones in the North Morowali Mine Area. American journal of engineering research (AJER), 12 (8), 49-53. https://www.ajer.org/papers/Vol-12-issue-8/12084953.pdf

Freyssinet, P. H., Butt, C. R. M., Morris, R. C., Piantone, P., 2005. Ore-Forming Processes Related to Lateritic Weathering, in: One Hundredth Anniversary Volume. Society of Economic Geologists, pp. 681–722. https://doi.org/10.5382/AV100.21

Gielen, Dolf., 2021. Critical materials for the energy transition. International Renewable Energy Agency.

Handika, E. T., Sutarto, S., & Soesilo, J., 2024. Geologi dan Karakteristik Laterit Nikel Berdasarkan Mineralogi Batuan Dasar dan Geokimia Daerah Routa dan Sekitarnya, Kecamatan Routa, Kabupaten Konawe, Provinsi Sulawesi Tenggara. Jurnal Ilmiah Geologi PANGEA, 11(2), 114-128. https://doi.org/10.31315/jigp.v11i2.14138

Hasria, H., Jaya, R. I. M. C., Awadh, S. M., Riskiyanti, R., Deniyatno, D., Syahrul, S., & Septiana, S., 2024. Mineralogy and Geochemical Characteristics of Lateritic Nickel Deposit in Wiwirano District, North Konawe, SE Sulawesi, Indonesia. The Iraqi Geological Journal, 171-183. https://doi.org/10.46717/igj.57.2C.13ms-2024-9-21

Haya, A., Conoras, W. A., & Firman, 2019, Penyebaran Endapan Nikel Laterit Pulau Obi Kabupaten Halmahera Selatan Provinsi Maluku Utara. Journal of Science and Engineering, 25-33. http://ejournal.unkhair.ac.id/index.php/josae

Irzon, R., 2017. Pengayaan Logam Berat Mn, Co, dan Cr pada Laterit Nikel di Kabupaten Konawe Utara, Provinsi Sulawesi Tenggara. Buletin Sumber Daya Geologi, 12(2), 71-86. https://doi.org/10.47599/bsdg.v12i2.37

Ito, A., Otake, T., Maulana, A., Sanematsu, K., Sufriadin, & Sato, T., 2021. Geochemical constraints on the mobilization of Ni and critical metals in laterite deposits, Sulawesi, Indonesia: A mass-balance approach. Resource Geology, 71(3), 255-282. https://doi.org/10.1111/rge.12266

Kadarusman, A., Miyashita, S., Maruyama, S., Parkinson, C.D., Ishikawa, A., 2004. Petrology, geochemistry and paleogeographic reconstruction of the East Sulawesi Ophiolite, Indonesia. Tectonophysics 392, 55–83. https://doi.org/10.1016/j.tecto.2004.04.008

Kementerian Energi dan Sumber Daya Mineral, 2024. Keputusan Menteri ESDM No 132.K/GL.01/MEM.G/2024.

Kementerian Energi dan Sumber Daya Mineral, 2023. Keputusan Menteri ESDM No 296.K/MB.01/MEM.B/2023.

Khairunnisa, Y., 2025. Perspektif Hukum Joint Venture in Foreign Direct Investment Indonesia-Korea Selatan dalam Industri Baterai Electric Vehicle (EV) Oleh PT HLI Green Power. Media Hukum Indonesia (MHI), 3(4), 264-274. https://doi.org/10.5281/zenodo.17462537

Langkoke, R., Thamrin, S. W. M., & Saffanah, Z., 2024. Nickel Element Content Distribution in Laterite Deposits Based on Geochemistry Using the Inverse Distance Weighting (IDW) Method. International Journal of Engineering and Science Applications, 51-56. https://doi.org/10.18280/ijesca.123456

Ma, M., Gao, H., Sun, Y., & Huang, M. 2015. The adsorption and desorption of Ni (II) on Al substituted goethite. Journal of Molecular Liquids, 201, 30-35. https://doi.org/10.1016/j.molliq.2014.11.024

Mamyrbayeva, K. K., Kuandykova, A. N., Chepushtanova, T. A., & Merkibayev, Y. S., 2024. Review on hydrometallurgical processing technology of lateritic nickel ore for the last 20 years in the world. Heavy non-ferrous Metals, 1, 13-21. 10.17580/nfm.2024.01.03

Mudd, G. M., & Jowitt, S. M., 2018. Global trends in low-grade ore processing. Ore Geology Reviews, 98, 1–10.

Ockwell, D., Byrne, R., Atela, J., Chengo, V., Onsongo, E., Fodio Todd, J., ... & Ely, A., 2021. Transforming access to clean energy technologies in the global south: learning from lighting Africa in Kenya. Energies, 14(14), 4362. https://doi.org/10.3390/en14144362

Qi, D. R., Lan, T. G., Shu, Q., Feng, Y., & Zhou, S. H., 2024. Nickel enrichment during lateritization of ophiolitic ultramafic rocks: A case study from the Kelurahan Pondidrha laterite profile in Sulawesi, Indonesia. Ore Geology Reviews, 170, 106140. https://doi.org/10.1016/j.oregeorev.2024.106140

Zakaria, Z., Sidarto, D., 2015. Aktifitas Tektonik di Sulawesi dan Sekitarnya Sejak Mesozoikum Hingga Kini Sebagai Akibat Interaksi Aktifitas Tektonik Lempeng Tektonik Utama di Sekitarnya. Jurnal Geologi dan Sumberdaya Mineral 16, 115–127.

Zhang, Y., et al., 2021. Technological challenges in processing low-grade ores. Minerals Engineering, 170, 107024.

Zhang, Z. F., Zhang, W. B., Zhang, Z. G., & Chen, X. F., 2025. Nickel extraction from nickel laterites: Processes, resources, environment and cost. *China Geology*, *8*(1), 187-213. https://doi.org/10.31035/cg2024124