



Mineralogical Controls on Scandium Enrichment in Nickel Laterites of Wolo, Southeast Sulawesi, Indonesia

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Abstract

Nickel laterite deposits, enriched in critical metals such as nickel (Ni) and scandium (Sc), have gained significant attention due to their economic and technological importance. This study investigates the mineralogical and geochemical factors that influence scandium enrichment within the nickel laterites of Wolo, Southeast Sulawesi, Indonesia. The research focuses on the distribution and accumulation of scandium within the laterite profile, with particular emphasis on the limonite zone, and explores the geochemical processes that contribute to this enrichment. Geochemical analysis of 12 samples from three drill holes reveals a progressive increase in scandium concentrations, from 9–14 ppm in unweathered harzburgite to a peak of 82 ppm within the limonite horizon. This enrichment is accompanied by a substantial rise in iron (Fe) content, which increases from 5.71–6.34 wt.% in the bedrock to 43.19 wt.% in the laterite zones. X-ray diffraction (XRD) analysis identifies goethite and gibbsite as the key minerals involved in scandium accumulation. Furthermore, a positive correlation is observed between scandium and iron oxides, particularly goethite, while a negative correlation is noted with magnesium oxide (MgO). This study provides an understanding of the geochemical mechanisms driving scandium enrichment and highlights the role of iron oxides in this process.

Keywords:

Mineralogy, Nickel laterite, Geochemical, Scandium enrichment, Indonesia.

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1. Introduction

Nickel laterites, formed through the prolonged chemical weathering of ultramafic rocks, are among the most economically significant sources of critical metals, including nickel (Ni), cobalt (Co), and iron (Fe). Recent studies have highlighted the presence of scandium (Sc) in lateritic nickel and cobalt ores, with notable examples in deposits such as those in Cuba and New Caledonia. The enrichment of scandium in tropical lateritic environments, particularly within the limonite horizon, has garnered significant interest due to its potential as a resource for advanced technologies (Carballo et al., 2018; Teitler et al., 2019; Tupaz et al., 2020).

Tropical weathering conditions, which prevail in regions like Southeast Sulawesi,

Indonesia, provide an ideal setting for forming nickel laterites and enriching scandium (Maulana et al., 2019; Ito et al., 2021; Onggang et al., 2021). This involves complex interactions between mineralogical transformations, geochemical processes, and climatic factors, resulting in the redistribution and concentration of scandium within weathering profiles (Golightly, 1981; Irfan et al., 2019). Scandium is commonly associated with iron- and aluminum-bearing minerals such as goethite and gibbsite, which dominate the limonite zone in laterite profiles (Teitler et al., 2019; Pena et al., 2019; Qin et al., 2020; Tamehe et al., 2024). These minerals play a pivotal role in scandium accumulation, with geochemical studies indicating that goethite can adsorb up to 80% of scandium in such deposits (Chassé et al., 2016; Levard et al., 2018).

The Wolo region, located within the East Sulawesi Ophiolite (Kadarusman et al., 2004), presents a unique opportunity to investigate scandium enrichment processes in nickel laterite deposits derived from ultramafic rocks, primarily peridotite (Onggang et al., 2021). Previous research in the area has established the presence of scandium within the limonite zone, but the specific mineralogical and geochemical controls influencing its distribution remain insufficiently understood. Moreover, the tectonic activity of Southeast Sulawesi and its implications for laterite deposit development add another layer of complexity to these enrichment mechanisms.

This study focuses on understanding the mineralogical and geochemical controls on scandium enrichment within the Wolo laterite deposits. By analyzing scandium concentrations in relation to major oxides, such as Fe, Al₂O₃, Cr₂O₃, and MgO, the research aims to unravel the mechanisms driving scandium accumulation in the limonite zone. Additionally, the study compares the enrichment patterns observed in Wolo with those of other well-known nickel laterite deposits worldwide, contributing to a broader understanding of scandium resource potential. This research aims to understand the processes governing scandium mobility and concentration in tropical weathering environments through detailed mineralogical and geochemical analyses.

2. Materials and Methods

The study was conducted in the Wolo area, Southeast Sulawesi, where the lithology predominantly consists of ultramafic rocks, metamorphic units, and surface deposits (Fig. 1). The ultramafic rocks, primarily composed of peridotite and dunite, have undergone extensive chemical weathering, forming distinct laterite profiles. These profiles are typically characterized by a limonite zone at the top, a transitional zone in the middle, and a saprolite zone in the lower sections, underlain by unweathered bedrock (Fig. 2). The weathering processes reflect the chemical alterations influencing the distribution of the region's critical minerals and rare earth elements.

Samples were collected from three drill hole cross-sections: DBA7220 (MN01), DLA5501 (MN07), and DLA8219 (MN09), representing distinct laterite profiles. The sampling was conducted using a vertical core-drilling technique

with 1-meter intervals along each profile. The sampling drive was supported by PT Ceria Nugraha Indotama (CNI). To ensure accuracy, duplicate pulp samples were prepared and analyzed for mineralogical and geochemical evaluations.

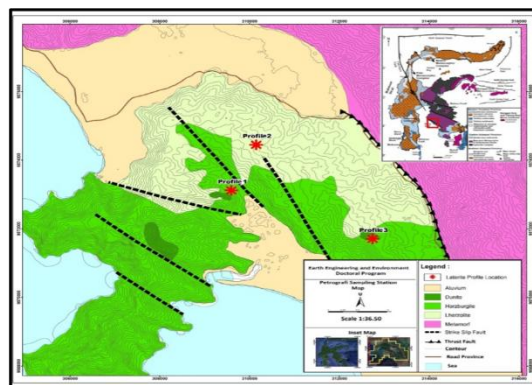


Fig. 1: Lithological map of the Wolo area, showing ultramafic rocks (dunite, harzburgite, lherzolite), metamorphic rocks, and surface deposits

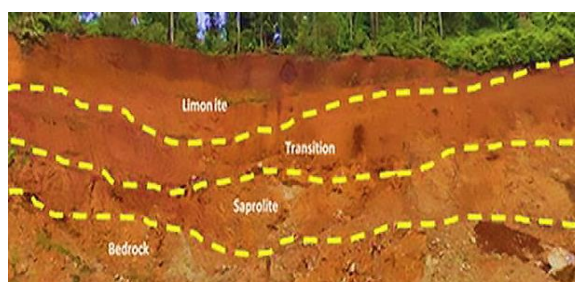


Fig. 2: Schematic representation of the laterite profile in the Wolo region, illustrating the sequential zones: limonite (upper part), transition, saprolite (middle and lower sections), and bedrock

Comprehensive laboratory analyses were conducted to characterize the mineralogical and geochemical features of the samples. Petrographic analysis of thin sections was performed to identify mineral assemblages and textural characteristics of the ultramafic bedrock. X-ray diffraction (XRD) analysis using a Shimadzu Maxima X-7000 instrument was utilized to identify the mineral phases within the limonite and saprolite zones, providing detailed insights into mineralogical transformations during laterization.

The geochemical characteristics of the samples were analyzed using two advanced techniques. X-ray fluorescence (XRF) analysis, performed with a Bruker S8 Tiger at the Sucofindo Laboratory, quantified major elements such as Ni, Co, and Cr. Inductively coupled plasma-optical emission spectroscopy (ICP-OES), carried out at Intertek, was employed to analyze scandium (Sc), yttrium (Y), and rare earth elements (REEs),

enabling a detailed understanding of their distribution within the laterite profiles.

3. Results and Discussion

Mineralogical Characteristics

The mineralogical composition of the ultramafic bedrock and associated laterite profiles was systematically analyzed using petrographic and X-ray diffraction (XRD) techniques. Three representative ultramafic rock samples, identified as MN01, MN07, and MN09, were examined to elucidate their mineral assemblages and textural features.

Sample MN01, classified as serpentinized dunite, predominantly consists of olivine (91%), orthopyroxene-enstatite (6%), and clinopyroxene-augite (<2%). This sample exhibits a holocrystalline structure with a phaneritic and inequigranular texture (Fig. 3a). In contrast, samples MN07 and MN09, both harzburgites, display slightly varying compositions. Sample MN07 contains 60% olivine, 36% orthopyroxene-enstatite, and <3% clinopyroxene-augite (Fig. 3b), whereas sample MN09 comprises 61% olivine, 33% orthopyroxene-enstatite, and <5% clinopyroxene-augite (Fig. 3c). Both harzburgite samples reveal porphyritic and inequigranular textures.

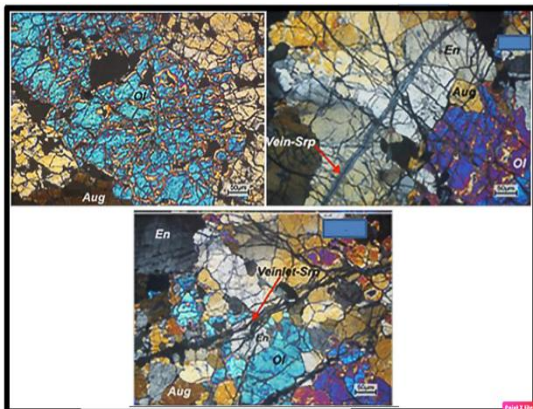


Fig. 3. Microphotography of thin section of bedrock; (a) MN01, (b) MN07, and (c) MN09, showing cumulate olivine (Ol), orthopyroxene-enstatite (En), and clinopyroxene-augite (Aug)

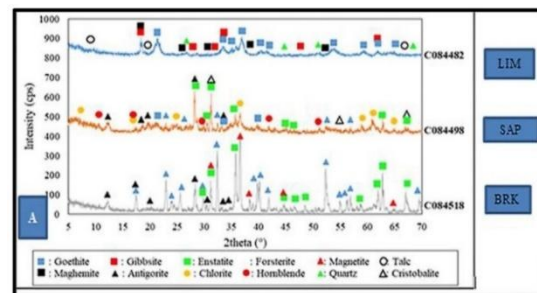
Additionally, XRD analysis was employed to characterize the mineral assemblages within the limonite and saprolite zones of the laterite profile. This detailed investigation highlighted the mineral types, textures, and distinct features associated with each horizon, providing concepts of their unique characteristics and interrelationships.

These analyses support understanding the mineralogical evolution and weathering processes within the laterite profile.

The X-ray diffraction (XRD) mineralogical patterns for the laterite horizons, specifically the limonite and saprolite zones, provide an understanding of their mineral composition, alteration processes, and the geochemical evolution of the profile. These patterns reveal the distinct mineral phases and transformations that occur as ultramafic rocks undergo laterization. Presents the XRD graphical patterns for three drill hole cross-sections, illustrating the mineralogical characteristics of each laterite horizon (Fig. 4).

In the limonite horizon, secondary iron oxides and hydroxides, such as goethite and gibbsite, dominate the mineral assemblage. These minerals form due to extensive silicate leaching and iron concentration, reflecting advanced weathering processes. The limonite zone comprises four primary minerals: goethite, gibbsite, magnetite, and quartz. Variations in mineral crystallinity and textural evolution are evident from the XRD patterns, with broad peaks indicating poorly crystalline or amorphous phases such as goethite, a characteristic product of advanced weathering.

In contrast, the saprolite horizon exhibits a mixture of primary minerals, including olivine and pyroxenes, alongside secondary phases like serpentine, smectite, and kaolinite. This mineralogical composition reflects an intermediate stage of weathering, where the ultramafic parent rocks are partially altered. The saprolite zone contains five primary minerals: enstatite, chlorite, antigorite, hornblende, and cristobalite. High crystallinity peaks in the saprolite horizon emphasize the preservation of primary minerals such as olivine and pyroxenes, providing evidence of less extensive alteration compared to the limonite zone.



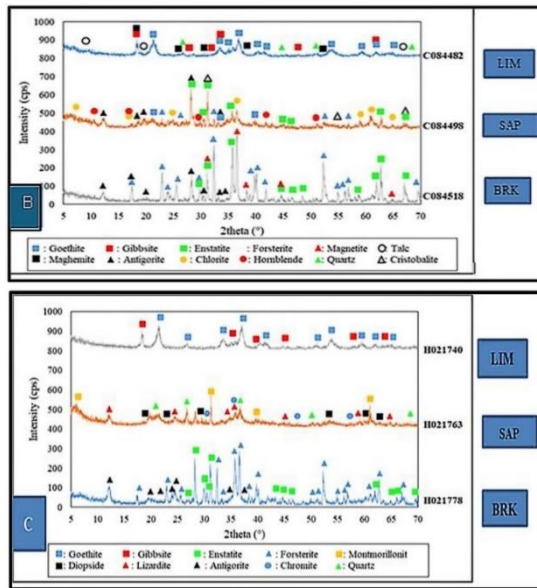


Fig. 4. Mineralogical graphic patterns: (a) MN01, (b) MN07, and (c) MN09

Distinct mineralogical variations across the laterite profile, as revealed by XRD patterns, reflect the progressive weathering and geochemical processes that shape each layer. The bedrock, predominantly composed of olivine minerals such as enstatite and forsterite, transitions upward into the saprolite layer, which displays an increasing dominance of clay minerals due to elemental mobilization and advanced weathering. The limonite layer, situated at the top of the profile, is characterized by intense weathering and residual concentration, resulting in the accumulation of iron oxide minerals like hematite (Fe_2O_3) and goethite ($\text{FeO}(\text{OH})$). This zone also contains talc, formed from the alteration of ultramafic minerals such as dunite, enstatite, and pyroxene, alongside gibbsite ($\text{Al}(\text{OH})_3$), a significant aluminum hydroxide mineral.

Scandium (Sc) can be structurally incorporated into goethite in nickel laterites and adsorbed on the goethite surface. Concurrently, yttrium (Y) is primarily adsorbed on goethite through bidentate-binuclear inner-sphere complexation. The striking disparity in speciation between Sc^{3+} and Y^{3+} , compared to Fe^{3+} in iron oxides, may result from differences in ionic radii (Qin et al., 2020). The presence of gibbsite is particularly noteworthy, as it is often associated with scandium, potentially acting as a carrier mineral in these nickel laterite deposits. Complementary geochemical analyses using ICP-OES and trace element distribution patterns further

elucidate the mechanisms driving scandium enrichment within the limonite layer.

4. Geochemical characteristics

Geochemical data from the Wolo laterite profile, showing the concentrations of major elements (Ni, Co, Fe, MgO, Al_2O_3 , SiO_2 , etc.) and rare earth elements (Sc, Y, Ce, Nd, Yb) in various horizons, are presented in Table 1. The data are divided by sample number, interval, and horizon type (limonite, transition, saprolite, and bedrock). For each sample, the table lists the concentrations of major elements in percentages or parts per million (ppm), with clear distinctions among limonite, transition, saprolite, and bedrock zones. The limonite zone generally shows high concentrations of iron (Fe) and scandium (Sc), which are most significant for scandium enrichment in the profile. Concentrations of elements such as Ni, Co, and Al_2O_3 also show variations across the profile, reflecting mineralogical transformations that occurred during weathering. These data indicate the different geochemical characteristics of each horizon and the potential of the limonite zone as a significant source of scandium.

The vertical distribution of geochemical elements within the laterite profile in the Wolo region provides essential insights into the mechanisms underlying scandium (Sc) enrichment. Depth-correlated diagrams (Fig. 5) illustrate variations in the concentrations of Sc, Fe, MgO, Al_2O_3 , and SiO_2 across the laterite profile, reflecting the laterization processes that transform ultramafic rocks under tropical weathering conditions. Geochemical analysis reveals systematic variations in element concentrations across the horizons. Scandium concentrations increase progressively from the bedrock through the saprolite zone and peak significantly in the limonite horizon, averaging 74 ppm over a thickness of approximately 16 meters, underscoring the limonite zone's potential as a substantial scandium reservoir. Similar trends are observed for Fe_2O_3 and Al_2O_3 , which correlate with scandium enrichment and are associated with the accumulation of iron oxides, such as goethite and aluminous minerals, such as gibbsite, due to intense leaching during weathering. In contrast, MgO concentrations decrease sharply from the bedrock through the saprolite zone, reaching minimal levels in the limonite horizon. This

inverse relationship suggests the breakdown of magnesium-rich primary minerals, such as olivine and pyroxenes, during laterization. SiO₂ concentrations exhibit minimal variability, indicating its limited mobility compared to other elements under these conditions.

The mineralogical composition of the limonite zone is critical to scandium accumulation, with high concentrations of goethite (FeO(OH)) and gibbsite (Al(OH)₃) being key contributors. Approximately 80% of scandium is adsorbed onto goethite surfaces, while the remaining 20% substitutes for Fe³⁺ ions in the hematite lattice (Qin et al., 2020). The positive correlation between scandium and Fe₂O₃ concentrations further underscores the primary role of goethite in scandium enrichment (Sanematsu et al., 2017). These geochemical characteristics align with patterns observed in nickel laterite deposits, such as those in Sorowako, Indonesia, and New

Caledonia. However, unique regional conditions in the Southeast Sulawesi Arm, including tectonic activity and the presence of overburden layers consisting of limestone, sandstone, and thin coal (Asfar et al., 2023), contribute to distinct variations in the profile development and chemical composition.

The geochemical behavior of scandium in the Wolo laterite profile highlights the significant role of iron oxides and aluminum hydroxides in its enrichment. The limonite horizon emerges as the most critical layer for scandium accumulation due to its mineralogical composition and geochemical stability. These findings provide valuable insights into scandium enrichment mechanisms in tropical weathering environments and establish the potential of the Wolo laterite deposits as a significant scandium resource.

Table 1: Geochemical composition of major and minor elements, as well as rare earth elements from the Wolo laterite profile

Pprofile	Sample No	Interval	Horizon	XRF											
				Ni	Co	Fe	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	Cr ₂ O ₃	MnO
				%	%	%	%	%	%	%	%	%	%	%	%
1	C092908	02.00 - 03.00	Limonite	0.83	0.080	43.19	0.06	2.06	12.83	6.04	0.00	0.05	0.18	2.83	0.95
	C092909	07.00 - 08.00	Transition	0.95	0.074	40.40	0.06	3.26	12.44	9.22	0.00	0.35	0.16	2.87	1.05
	C092926	12.00 - 13.00	Saprolite	0.80	0.023	12.69	0.07	17.80	3.66	52.51	0.00	1.15	0.03	1.04	0.25
	C092935	18.00 - 19.00	Bedrock	0.24	0.012	6.06	0.08	42.89	1.64	44.25	0.00	1.57	0.01	0.47	0.12
2	H021740	03.00 - 04.00	Limonite	0.80	0.138	40.90	0.06	1.27	17.92	3.37	0.00	0.01	0.40	2.41	1.02
	H021756	17.00 - 18.00	Transition	1.18	0.102	28.84	0.05	2.56	10.96	30.92	0.00	0.01	0.24	1.81	1.06
	H021763	21.46 - 22.00	Saprolite	2.23	0.031	16.95	0.06	14.53	7.13	42.44	0.00	0.34	0.15	1.28	0.40
	H021778	31.00 - 32.00	Badrock	0.22	0.015	6.34	0.06	36.52	2.60	45.64	0.00	2.64	0.06	0.44	0.12
3	C084482	04.00 - 05.00	Limonite	1.40	0.138	41.57	0.01	1.34	14.72	2.72	0.16	0.05	0.19	2.72	1.20
	C084486	08.00 - 09.00	Transition	1.19	0.275	42.58	0.01	1.48	10.94	6.29	0.16	0.07	0.12	2.66	1.93
	C084498	17.00 - 18.00	Saprolite	2.32	0.022	10.48	0.01	26.77	2.38	44.89	0.17	1.35	0.04	0.84	0.24
	C084517	26.00 - 27.00	Badrock	0.32	0.016	5.71	0.01	44.51	1.05	42.80	0.15	1.08	0.02	0.42	0.15

Pprofile	Sample No	Interval	Horizon	ICP-OES				
				Sc	Y	Ce	Nd	Yb
				ppm	ppm	ppm	ppm	ppm
1	C092908	02.00 - 03.00	Limonite	79	4.5	4.3	1.6	0.8
	C092909	07.00 - 08.00	Transition	77	6.8	2.8	2	1.4
	C092926	12.00 - 13.00	Saprolite	22	0.8	0.2	0.05	0.3
	C092935	18.00 - 19.00	Bedrock	11	0.7	0.05	0.05	0.1
2	H021740	03.00 - 04.00	Limonite	78	6.6	5.5	1.4	1.1
	H021756	17.00 - 18.00	Transition	56	96	0.2	11.8	9.4
	H021763	21.46 - 22.00	Saprolite	34	38.6	0.05	0.8	1.6
	H021778	31.00 - 32.00	Badrock	14	2.2	0.05	0.1	0.3
3	C084482	04.00 - 05.00	Limonite	82	1.9	2.2	0.6	0.8
	C084486	08.00 - 09.00	Transition	60	6.3	10.4	1.5	1.6
	C084498	17.00 - 18.00	Saprolite	17	0.9	0.2	0.1	0.2
	C084517	26.00 - 27.00	Badrock	9	0.8	0.05	0.05	0.2

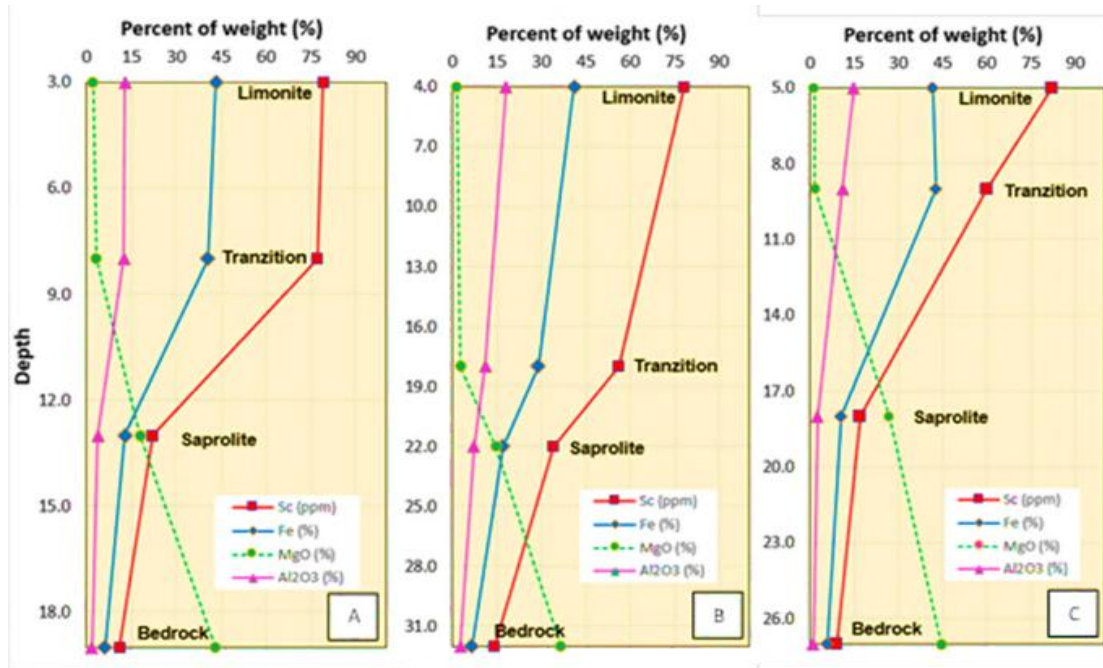


Fig. 5: Diagram of the distribution pattern of geochemical elements showing the relationship between the content of elements Sc, MgO, Fe, Al₂O₃, and the vertical depth (m) of (a) MN01, (b) MN07, and (c) MN09

The geochemical behavior of scandium within the laterite profile reveals distinct patterns of association with certain oxides, while others exhibit no such relationship. For instance, elements like Ni, SiO₂, and CaO show no correlation with scandium, implying that their distribution is governed by differing geochemical processes or mineralogical associations.

In contrast, a clear positive linear correlation between scandium and oxides such as Fe, Al₂O₃, and Cr₂O₃ (Fig. 6). This suggests that scandium preferentially accumulates in zones enriched with these oxides, likely due to its ability to substitute within the crystal lattices of iron- and aluminum-bearing minerals, such as goethite, hematite, or aluminous clays—common constituents of weathered environments. Its correlation with Cr₂O₃ may further indicate an affinity for chromium-bearing phases like chromite, which persist or form during the lateritization process.

Additionally, scandium exhibits an inverse exponential relationship with MgO, where decreasing MgO content corresponds to increasing scandium concentration. This trend can be attributed to the breakdown of magnesium-rich primary minerals, such as olivine and pyroxenes, during weathering. As these minerals degrade, scandium is mobilized and subsequently

incorporated into secondary minerals more stable under lateritic conditions, such as iron

oxides or aluminous clays. This interplay underscores the complex geochemical processes driving scandium enrichment within a lateritic profile.

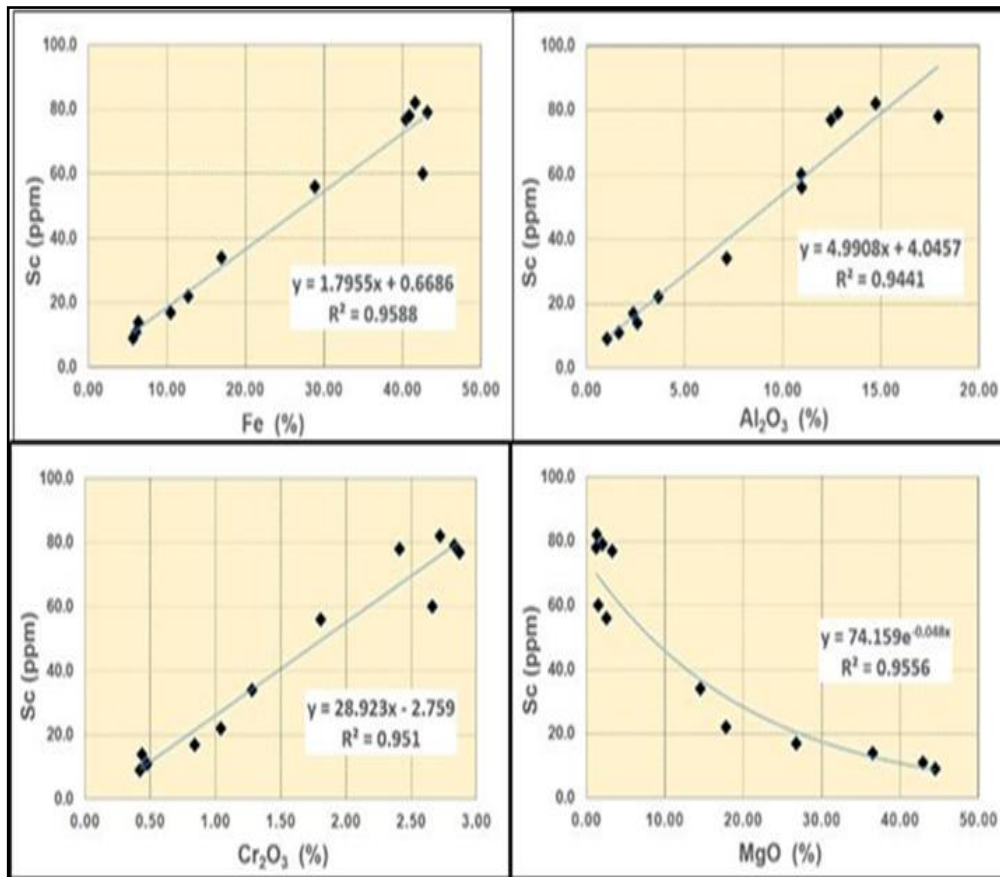


Fig. 6: Geochemical plot diagram showing the relationship between Scandium and Fe, Al₂O₃, Cr₂O₃, and MgO from the Wolo laterite profile

5. Scandium Enrichment in the Lapaopao Laterite Profile

The enrichment of scandium (Sc) in the laterite profile of Wolo is closely associated with the presence of high concentrations of goethite (FeO(OH)) and gibbsite (Al(OH)₃) in the limonite zone, emphasizing the key role of iron oxides and alumina that result from the weathering of ultramafic rocks. Mineralogical analyses of the laterite samples confirm that goethite and gibbsite dominate the limonite zone, with scandium predominantly enriching the iron oxide phases, particularly goethite. This pattern aligns with other studies on laterite deposits, such as those in Sorowako, where scandium content shows a positive correlation with Fe₂O₃ concentrations (Sanematsu et al., 2017). Research indicates that approximately 80% of scandium is adsorbed onto goethite, while the remainder is incorporated into hematite's crystal lattice, substituting Fe³⁺ ions (Qin et al., 2020).

In the Wolo area, scandium concentrations show a marked increase across the laterite profile, from 9.8 ppm in the harzburgite protolith to 82 ppm in the red limonite zone. This enrichment is consistent with findings in other regions, such as New Caledonia, where scandium levels range from less than five ppm in dunite to more than ten ppm in lherzolite (Teitler et al., 2019). Unlike most laterite deposits, the laterites in the Southeast Sulawesi region exhibit a distinct profile, with tectonic activity in the Southeast Sulawesi region playing a crucial role in the formation of these unique laterite deposit profiles (Asfar et al., 2023).

The substantial enrichment of scandium is attributed to the high capacity of goethite to absorb scandium, whereas hematite exhibits limited scandium absorption due to its structural constraints. Crystal-chemical factors are critical in scandium distribution in laterite deposits formed from ultramafic rocks. Identified three main

factors that influence scandium enrichment in laterites derived from mafic and ultramafic rocks: (i) the initial scandium content of the parent rock, (ii) prolonged tropical weathering leading to the formation of yellow limonite dominated by goethite, and (iii) local remobilization of scandium through the dissolution and recrystallization of goethite and its partial replacement by hematite (Qin et al., 2020; Teitler et al., 2019). This remobilization can result in a reduction in scandium concentrations within the yellow limonite horizon.

6. Conclusion

The conclusion of the study on scandium enrichment in nickel laterite deposits at Wolo, Southeast Sulawesi, can be summarized as follows:

1. The scandium (Sc) enrichment concentration increases gradually from 9–14 ppm in unweathered harzburgite to a peak of 82 ppm in the limonite horizon in the laterite profile.
2. This geochemical enrichment trend is associated with a significant increase in iron (Fe) content, from 5.71–6.34 wt.% in the basement rock to 43.19 wt.% in the laterite zone, indicating a strong geochemical relationship between scandium and iron
3. Mineralogical factors based on petrographic and XRD analysis indicate that goethite and gibbsite are the main minerals responsible for accumulating scandium in the laterite profile.
4. Geochemical relationships based on positive correlations between scandium and iron oxides, especially goethite, were observed. In contrast, negative correlations occurred with magnesium oxide (MgO), indicating that iron oxides are important in the scandium enrichment process in laterite zones.

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petrography, and XRF), and Intertek for their support with ICP-OES analysis

8. Conflict of Interest

The authors declare that there are no conflicts of interest.

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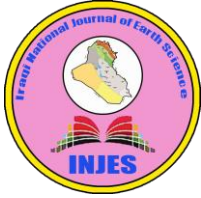
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الضوابط المعدنية لإثراء السكانديوم في لاتيريت النيكل في وولو، جنوب شرق سولاويسي،

إندونيسيا

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الملخص

تتكشف صخور الكاربونات بشكل جيد في قبة سنام الملحية. أظهرت الدراسة الصخرية ان الغالبية العظمى لعينات صخور الكاربونات هي دولومايت. وقد تم جمع عشر عينات من صخور الدولومايت من ثلاث محطات محددة لمعرفة خصائصها البتروغرافية والجيوكيميائية من اجل تحديد اصل هذه الصخور. تتكون صخور الدولومايت بشكل رئيس من معادن الدولومايت والكوارتز والجبس ويشكل ثانوي من الباياريت واكاسيد الحديد والكالسايت والفلسبار كنتيجة لعمليات التغيير وتأثير السوائل الحارة. يعد دولومايت سنام من النوع شبه النقي مع وجود الجبس والفلسبار القلوي كشوائب. ان عدم وجود الحفريات والمادة العضوية تدعم الأصل الكيميائي لهذه الصخور. اظهر التحليل الجيوكيميائي للعناصر الرئيسية والنادرة ان الدولومايت قد تشكل في بيئة بحرية (بيئة المد الى فوق المد) تحت ظروف اختزالية. يمكن ان تعزى عملية الدلمة الى ارتباطها ببيئة السبخة بدليل عدم وجود الحفريات والمسامية والمحاليل الملحية ووجود المتبخرات وانعدام وجود المتحجرات. اظهر التحليل الجيوكيميائي للعناصر الأرضية النادرة والشذوذ السلبي لكل من السيريوم واليورانيوم الى ان توزيع هذه العناصر في الدولومايت يشبه نمط توزيعها في مياه البحر. ان التغييرات واسعة التأثير على صخور قبة سنام قد نتجت من التأثير المكثف للمحاليل الحارة الثانوية، كنتيجة للأنشطة المتكررة للصهارة وحركة الاملاح.

الكلمات المفتاحية:

علم المعادن، لاتيريت النيكل، الكيمياء الجيولوجية، تخصيب سكانديوم، إندونيسيا.

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