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IMPLICATION OF FRACTURE DENSITY ON UNSERPENTINIZED ULTRAMAFIC ROCKS TOWARD CHARACTERISTICS OF SAPROLITE ZONE IN SOROWAKO, SOUTH SULAWESI

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ABSTRACT

Usage of nickel-containing materials has increased over time in accordance with economic growth. The largest worldwide nickel resources occur in surface laterite deposits that have formed during chemical weathering of ultramafic rocks where the area that represent one of largest nickel reserves in Indonesia is Sorowako. This study aims to identify the characteristics of saprolite zone on unserpentinized ultramafic-hosted of nickel laterite deposit in Sorowako. Based on depth profile of nickel content in lateritic deposit, it is known that the Ni grades reach a maximum in saprolite zones so that identification of factors affecting the characteristics of saprolite zone is indispensable. Fracture density on ultramafic bedrocks played the important roles during laterisation and each fractures density type has the implication toward the saprolite zones. By classification of fracture density, high to medium fractured types of bedrocks indicated the thick saprolite zone while the low to unfractured types are thinner. Saprolite zones of high to medium fractured type are more silicified than others due to the originality of silica accumulation occupied along opening fractures and joints. High silica content which is commonly present on lower layer of saprolite zone should to be aware especially when the Ni grade still above the cut-off which potentially affected to ore grade dilution.

Keywords: laterite, chemical weathering, ultramafic rocks, saprolite, unserpentinized

ABSTRAK

Penggunaan material berbahan nikel telah mengalami peningkatan dari waktu ke waktu seiring dengan pertumbuhan ekonomi. Sumberdaya nikel terbesar di dunia terjadi pada endapan laterit di permukaan yang terbentuk selama proses pelapukan kimiawi dari batuan ultramafik dimana salah satu lokasinya dengan tingkat cadangan nikel terbesar di Indonesia berada di Sorowako. Studi ini bertujuan untuk mengidentifikasi karakteristik zona saprolit endapan nikel laterit pada batuan ultramafik tak terserpentinisasi di Sorowako. Berdasarkan profil kedalaman terhadap kandungan nikel pada endapan laterit, telah diketahui bahwa kadar Ni mencapai maksimum dalam zona saprolit sehingga identifikasi terhadap faktor-faktor yang mempengaruhi karakteristik zona saprolit sangat diperlukan. Densitas rekahan pada batuan ultramafik berperan penting selama proses lateritisasi dan setiap tipe densitas rekahan memiliki implikasi terhadap zona saprolit. Melalui klasifikasi densitas rekahan, tipe rekahan berdensitas tinggi hingga sedang pada batuan dasarnya mengindikasikan zona saprolit yang tebal sedangkan zona saprolit pada tipe densitas rekahan rendah hingga tanpa rekahan lebih tipis. Zona saprolit dengan tipe rekahan tinggi hingga sedang lebih tersilisifikasi dibandingkan dengan tipe lainnya disebabkan oleh akumulasi alamiah dari silika yang bertempat di sepanjang bukaan rekahan atau kekar. Kandungan silika tinggi yang umumnya terdapat di lapisan bawah zona saprolit seharusnya diwaspadai terutama ketika kadar Ni-nya masih diatas ambang keekonomian yang berpotensi menyebabkan dilusi pada kadar bijih.

Kata kunci: *laterit, pelapukan kimiawi, batuan ultramafik, saprolit, takterserpentinisasi*

INTRODUCTION

Nickel is often dubbed a hidden metal because of its invisible existence. In fact, nickel is applied over 300,000 objects that are close to human daily life. About 65% of nickel is used in the stainless-steel industry. Cutlery is the most easy-to-find application of stainless steel with the composition of 18% chromium and 10% nickel. Cupronickel as an alloy of copper that contain 75% of copper and 25% of nickel is commonly used as a coin-making material worldwide including the coins used by many people for selling-buying transaction on real market.

The world nickel resource on land is approximately 60% in laterites deposit type and the rest of 40% is in sulfide deposit type (USGS Commodity Summaries, 2016). Historically, the abundance of nickel laterites resources is not followed by the large portion of world nickel production that in fact dominated by sulphide deposit. This condition in positive perspective is the opportunity to begin optimizing nickel laterite production through the improvement especially in terms of processing technology.

Nickeliferous ores originated from sulfide are typically derived from volcanic or hydrothermal process while laterite ores are formed near the surface following extensive weathering (Mudd, 2009). The large potential resource of nickel which is originated from laterite has been made many researchers working on to understand the weathering process on laterite deposit and supergene enrichment over ultramafic rocks (Burger, 1996; Brand et al., 1998, Gleeson et al., 2003; Butt and Cluzel, 2013). Formation of nickel laterites are influenced by multiple factors including bedrock geology, climate, age of weathering, and geomorphology (Butt and Cluzel, 2013). Nickel laterite development involves dissolution of the primary minerals of the peridotite, which leads to leaching of soluble elements (Si, Mg) and in situ neoformation of mineral phases (mainly oxy-hydroxides) that host the insoluble elements (Fe, Al and Cr) (Quesnel et al., 2017).

Based on the chronology, the initial weathering is beginning along fractures and joint in the bedrock. Chemical attack and weathering is also proceeding along joints and fractures in the rock and cleavages and micro-fractures in the crystals. Most commonly serpentines or garnierites can be seen as replacement product of the original mineral or neo-formed in fractures and other rock opening. Silica as diluted material is also deposited along the fractures in the peridotite and will ultimately result in the formation of silica box-work as the peridotite converts to limonite. By these facts, fractures and other opening rocks play an important role in attacking waters and assisting in taking dissolved material away from the weathering system. The process of weathering started along joint and fracture surface and has resulted in the formation of "boulders" within the saprolite zone. Original texture is still recognizable and the weathered profile has not collapsed yet.

This paper focuses to assess the implication of fracture density on bedrock in correlation with characteristics of saprolitic horizon distribution and nickeliferous ores especially for unserpentinized ultramafic-hosted

LOCATION AND GEOLOGICAL SETTING

Sorowako ultramafic complex is located about 600 km from Makassar, a provincial city of South Sulawesi whereas administratively part of East Luwu regency. This ultramafic complex is a part of East Sulawesi Ophiolite (ESO) which is tectonically dismembered and cropped out over 10,000 km^2 in the eastern Sulawesi (Monnier et al., 1995).

East Sulawesi Ophiolites is one of four distinct lithotectonic belts of the K-shape island of Sulawesi. The others from west to east are the West Sulawesi Tertiary Magmatic Arc and associated sediments, the Central Sulawesi Metamorphic Belt and accreted continental fragments of Banggai-Sula islands and Tukang Besi-Buton platforms (Hall and Wilson, 2000; Kadarusman *et al.*, 2004). Ultramafic rocks are the most common constituents of ESO with varieties rocks of lherzolite, harzburgites, dunite and pyroxenites. Peridotite covers 70% of the ophiolite in Sulawesi and lherzolite is the most abundant and the rest consist of harzburgite and dunite. Sorowako region has unique composition of peridotite which is different with another ophiolite in Sulawesi. Only in Sorowako, the harzburgite and dunite is more dominant than lherzolite (Kadarusman et al., 2004). In addition, in the Sorowako region, the bedrock is essentially unserpentinized where serpentine being only restricted to border of joints as thin rim or as fine-grained matrix of tectonic breccias (Soeria-Atmadja *et al*., 1974).

Tectonically, Sorowako region has undergone multiple events from Paleogen to Neogen. The area is interconnected with the extreme complex of Matano fault zone. Intimately mixed ultramafic rocks and Mesozoic sediments of mid Miocene subduction mélange of East Sulawesi rest against the presumably pre- or early Triassic metamorphic complex of eastern Central Sulawesi. The west-northwest trending zone of the Matano fault zone has the fault segments that consistently step to left and are associated with the pull-apart basin on Lake Matano along with in-line grabens and sags (Silver et al., 1983, Simandjuntak et al., 1991).

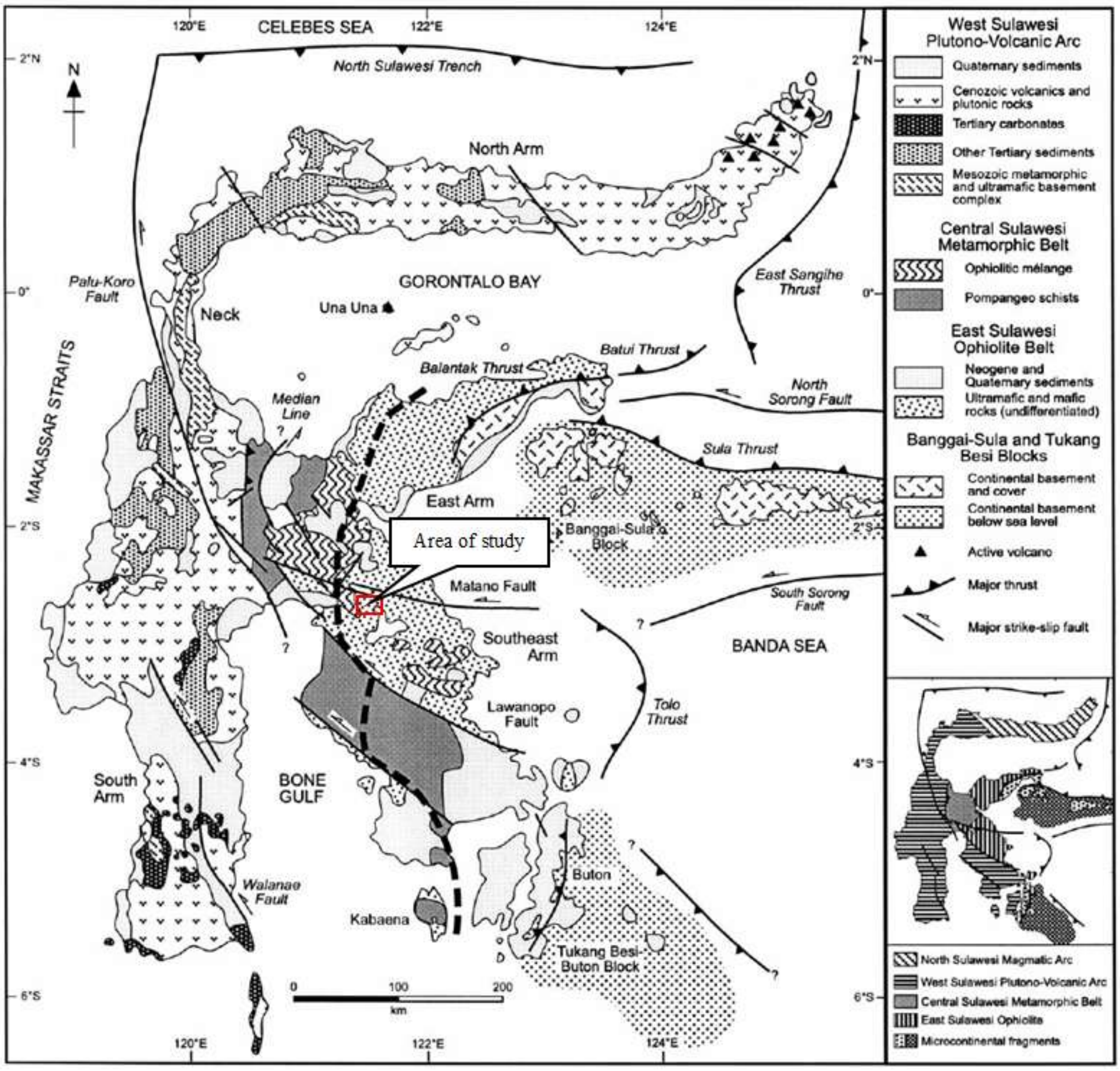


Fig. 1. Geology map of Sulawesi. Inset map shows the principle tectonic provinces (modified from Hall and Wilson, 2000).

METHODS

Linear Fracture Frequency (FF)

The (Linear) Fracture Frequency is basically the ratio of a number of fractures, counted by geologist, divided by the sample length (Seguret & Guajardo, 2015). Parameter of FF is one dimensional of fracture density that useful to characterize the fracture distribution from drilled core. The determination of FF is not easy-calculated because of the crushed materials on significant part of actual samples. The simplify equation of linear fracture frequency or called as fracture density from drilled core as follows:

$$FD = \frac{n}{L_T} x\ 100\% \qquad (1)$$

where: n = number of fraction intersection
L_T = total length of drill run

Rock Quality Designation (RQD)

Rock Quality Designation (RQD) is a semi-quantitative measure of fracture density which can be estimated from core recovery data (Singhal & Gupta, 2010). By original definition, RQD is the length in percent of measured length of the unweather drill core bits longer than 10 cm (Deere, 1988).

RQD parameter is a method that more easy and quick to measure by geologist compared with fracture density. This method frequently applied in core logging that often used for measuring the jointing density along the core drill hole. The illustration for calculating RQD from drilled core is shown on Figure 2.

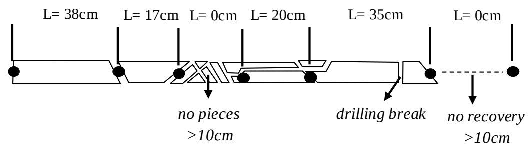


Fig. 2. Illustration for RQD Logging (modified from Deer, 1988)

The following simplify equation formulated to for calculating RQD from drilled core.

$$RQD = \frac{\sum_{i=1}^{N} Li}{L_T} x100\% \qquad (2)$$

where,
Li = length of i^{th} drill core longer than twice the core diameter,
L_T = total length of drill run,
N = number of core pieces longer than twice the core diameter (used 10cm length)

RESULTS AND DISCUSSION

Lateritic zone

There are two local hills in Sorowako mining area where the study has worked. Topographically, these two hills have similar landform type. All drilled cores as the input data were mainly provided by PT Vale Indonesia that consists of 192 holes (Fig 3). Drilling configuration that has been done has the regular grid pattern of 50 m. Total of 5,368 core samples intercept were produced from this program and all the samples were analyzed using X-Ray Fluorescence spectrometry.

Assay data resulted from the XRF analysis were validated for geological domaining process to determine the layering of laterite zone –limonite, saprolite and bedrock. The example of chemical concentration of laterite layer from drillhole data is shown on Table 1. The important point during determining geological domain on nickel laterite deposit is how to understand the basic geological concept on chemical weathering of nickeliferous lateritic deposit.

In general, the complete profile of nickel laterite deposit consists of three layers: (i) limonite; (ii) saprolite and (iii) bedrock. The base profile mostly consists of unweathered bedrocks as the original rocks prior to weathering. Less part of weathered protolith in bedrock usually occurred within the rock openings or fractures/joints. The incipient weathering is just beginning along these fractures/joints in the rock.

Tabel 1
Example of chemical concentration of laterite profile

Hole_Id	Depth Interval (m)	Ni (%wt)	Fe (%wt)	SiO2 (%wt)	MgO (%wt)	Layer	Rock Type	Serp	Primary Mineral	Secondary Mineral	Tertiary Mineral	Remarks
A-006	0.00-0.30	-	-	-	-	Lim						Cut :0.30m
A-006	0.30-1.00	1.30	42.50	8.60	2.00	Lim			hmt			OB
A-006	1.00-2.00	1.36	40.50	11.30	3.00	Lim			hmt	sil	mng	mgl
A-006	2.00-3.00	1.50	37.10	20.70	3.40	Lim			mng	sil	gth	ssp
A-006	3.00-4.00	1.57	30.50	29.00	6.30	Sap			mng	sil	gth	ssp
A-006	4.00-5.00	2.28	29.20	25.70	6.50	Sap			gth	mng	sil	ssp
A-006	5.00-5.40	2.33	25.70	28.00	8.20	Sap			gth	mng	sil	ssp
A-006	5.40-5.55	1.06	13.23	29.57	20.31	Sap			olv	px	sil	bld
A-005	5.55-6.00	2.19	21.60	33.30	14.20	Sap	Hrz	nil	gth	mng	sil	ssp
A-005	6.00-7.00	2.33	22.20	32.80	15.60	Sap			gth	mng	sil	ssp
A-006	7.00-8.00	1.96	17.00	37.90	17.40	Sap			gth	mng	sil	ssp
A-006	8.00-9.00	1.79	15.99	37.38	16.53	Sap			gth	mng	sil	bld in ssp
A-006	9.00-10.00	1.78	12.87	40.12	22.51	Sap			gth	mng	sil	bld in ssp
A-006	10.00-11.00	1.21	11.96	36.80	25.57	Sap	Hrz	low	gth	olv	px	rocky sap
A-006	11.00-11.35	1.57	9.78	41.68	24.29	Sap	Hrz	low	olv	px	sil	hard sap
A-006	11.35-12.00	0.34	7.00	36.80	35.70	Sap	Hrz	nil	olv	px	sil	bld
A-006	12.00-13.00	0.99	9.91	38.10	26.07	Sap	Hrz	low	olv	px	gth	hard sap
A-006	13.00-14.00	0.90	8.80	39.26	27.79	Sap	Hrz	low	olv	px	sil	hard sap
A-006	14.00-15.00	0.51	9.43	39.39	28.58	Brk	Hrz	low	olv	px	sil	hard sap
A-006	15.00-16.00	0.36	9.40	34.40	32.00	Brk	Hrz	nil	olv	px	sil	brk
A-006	16.00-17.00	0.28	6.20	36.50	37.00	Brk	Hrz	nil	olv	px	sil	brk
A-006	17.00-18.00	0.38	8.03	44.62	22.79	Brk	Hrz	nil	olv	px	sil	brk
A-006	18.00-19.00	0.30	6.60	38.11	31.48	Brk	Hrz	low	olv	px	sil	brk,EOH:19m,AVGMGS:0.95,RQD:51.25%,WT:3

lim: limonite; sap: saprolite; brk: bedrock; hrz: harzburgite; hmt: hematite; mng: manganese; gth: goethite; sil: silica; olv: olivine; px=pyroxene; ob=overburden; mgl: medium grade limonite; ssp: soft saprolite; bld: boulder

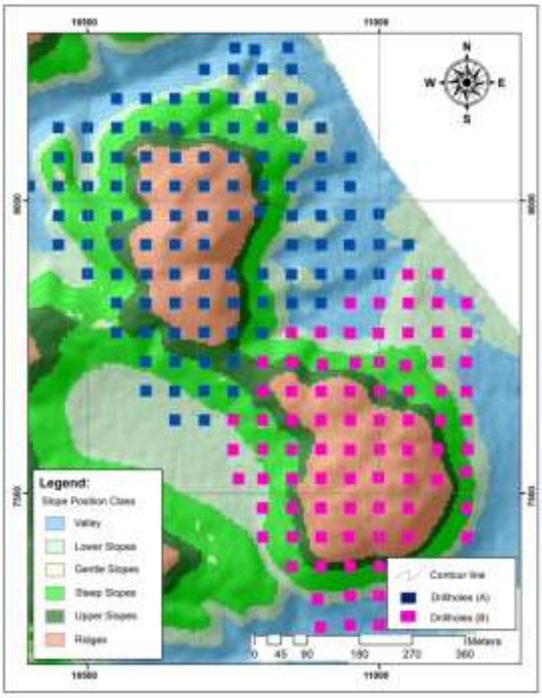


Fig. 3. Drillhole distribution with the total amount of 192 sites.

The overlying layer with mostly brownish yellow in color is saprolite. The layer contains mix-composition between soil and original rock textures and structure that are still preserved. Common observed minerals within the layer are goethite, manganese and silica. Garnierite and silica found within veins or fractures. The division between bedrock and saprolite may not be very sharp due to the variability of "weathering front" contour which penetrates at sites of faults, fractures and major joints.

Limonite layer is the top profile on lateritic weathering deposit. The upper part of this zone is rich of hematite and goethite at the lower one. The original textures and structures of rock are completely obliterated due to collapse (see Figure 4).

Fig. 4. Laterite profile of unserpentinized ultramafic rock on Sorowako mining face.

Fracture frequency distribution

Based on the linear fractures frequency or fracture density and rock quality designation value from drilled core data, the area of study has the different bedrock characteristic between location A and B. Bedrocks on location A is dominated by high to medium fracture frequency. In contrast, location B is mostly characterized by low fractured and even tend to un-fractured.

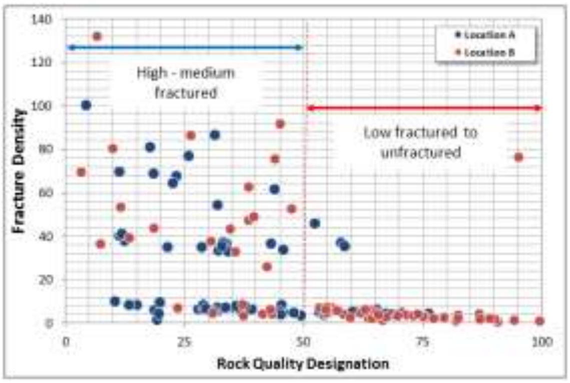


Fig. 5. Plots distribution of fractures from drilled core

Plots of fracture data from drilled core on area of study as shown on Fig 5 indicate the different fractures population distribution. The summary statistic of fractures data calculated from the data set is shown in Table 2.

Tabel 2
Summary statistics of fractures data set

Properties	Variable	Location A	Location B
Rock Quality Designation (RQD)	N	105	87
	Min	1.67	3.33
	Max	76.33	100.00
	Mean	34.91	54.49
	S.Dev.	18.19	25.32
Fracture Density (FD)	Min	1.27	0.44
	Max	100.00	132.16
	Mean	23.73	20.42
	S.Dev.	26.65	29.34

In facts, the difference type of fractures density impacted to the difficulties during mining operation. The big size boulder with low fractures or even un-fractured on lower saprolite or upper bedrock can cause the lower mining recovery due to the limitation of existing big mining fleet operation.

Implication toward saprolite characteristics

Implication of different fracture characteristics has been evaluated to identify the impact to the lateritic horizons distribution and also chemical composition profile. Based on the frequency distribution, variable of limonite thickness indicated the absence correlation as the impact of different fracture characteristics (Fig 10).

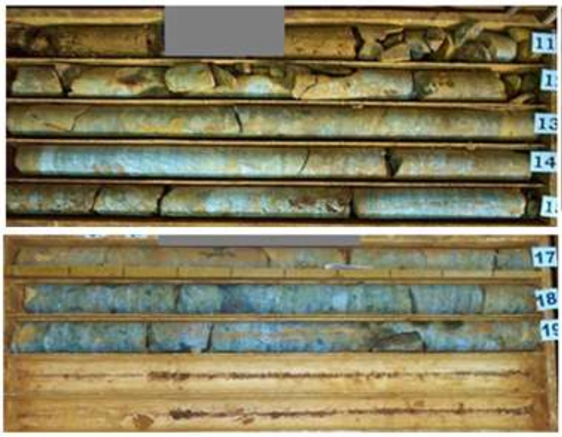


Fig. 6. Example of low fractured to un-fractured type based on drilled core data

Fig. 7. Outcrops of low fractured ultramafic rock in mining face

Fig. 8. Example of medium fractured type based on drilled core data

Fig. 9. Outcrops of medium fractured ultramafic rocks

On the contrary, saprolite thickness population shows difference pattern where the mode as the most frequently occurring thicknesses value on location A is thicker than location B (Fig 11). This represented mode value for both locations is confirming that the area with more high fractured on the bedrocks indicated the deeper penetration of chemical attack which resulted the thicker of saprolite zone than the opposite. The statistic summary for each laterite horizon thickness depicted on Table 3 also represent the similar trend for the mean value of thickness both limonite and saprolite zone for each difference fracture type.

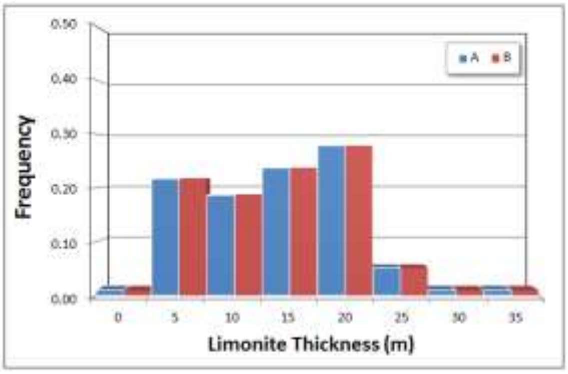


Fig. 10. Histogram distribution of limonite thickness

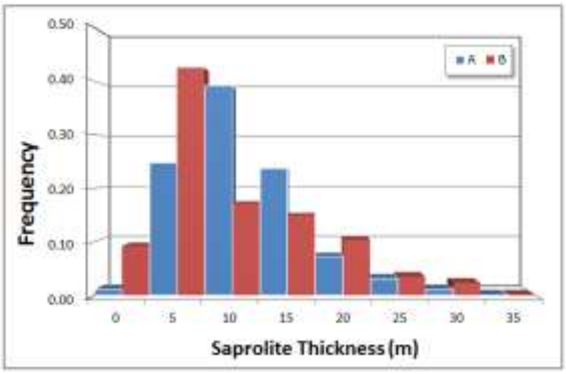


Fig. 11. Histogram distribution of saprolite thickness

Tabel 3
Summary statistics of layer thickness

Layer	Variable	Location A	Location B
Limonite	Min	0.00	0.50
	Max	35.00	31.00
	Mean	11.98	11.26
	St.Dev.	6.89	7.55
Saprolite	Min	0.00	0.00
	Max	29.00	27.00
	Mean	8.99	7.36
	St.Dev.	5.55	7.14

Chemical composition of Fe-Si-Mg in saprolite zone for both two types of fracture is depicted on Figure 11. Based on the ternary diagram, location A has higher silica content than location B. By the originality of silica accumulation, the availability of free space within the rocks along fracture opening or natural joints will be occupied by silica and it is confirming that the location A with the dominant characteristic of high to medium fractured within the bedrocks has higher content of silica than location B.

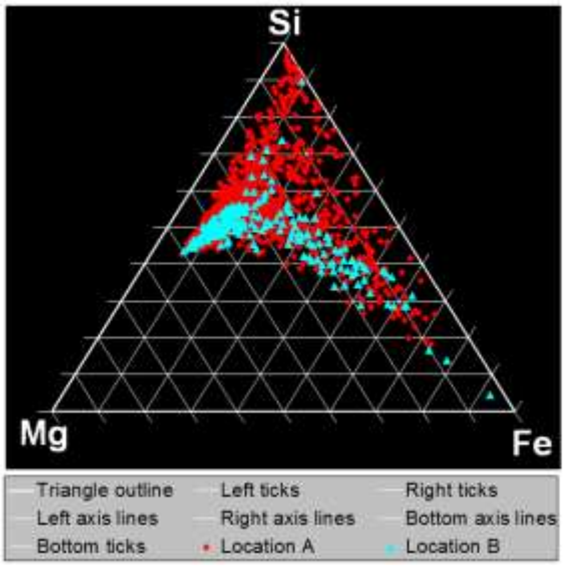


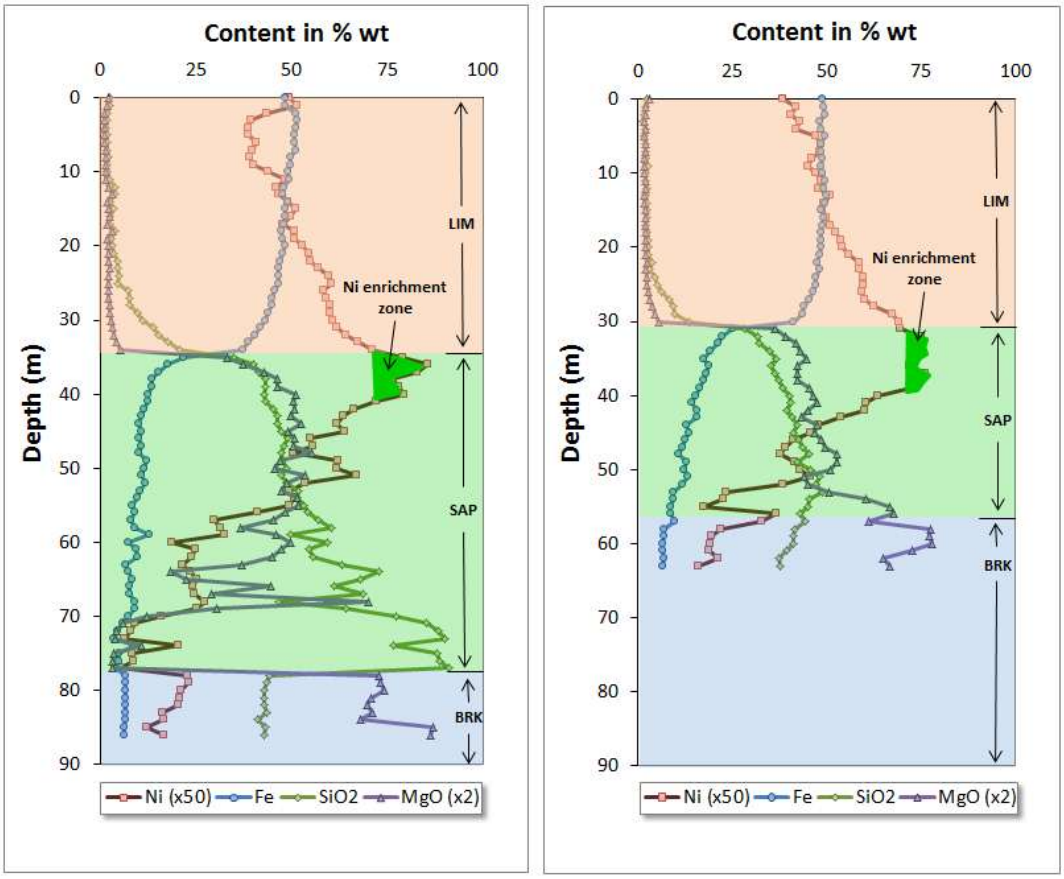
Fig. 12. Ternary diagram Fe-Si-Mg of saprolite zone

In the laterite profile, silica is associated as a box-work, sheet formed and lenses that are emplaced within limonite and saprolite zones while in another way as massive silica. The box-work or sheeted silica are generally oriented sub-horizontally at the time of formation and indicates the precipitation of silica at water table level (Ahmad, 2009).

Fig. 13. Typical high silica content within hard saprolite

Vertical variation of chemical composition

The characteristic of depth profile composition between two locations are shown on Figure 14 represented the area of high-medium fractured bedrock and low to un-fractured bedrock. In high to medium fractured (Location A), the depth concentration of Fe-SiO_2-MgO shown the normal variation of nickel laterite profile. The typical of high intense of fractures are displayed on lower layer of saprolite zone. The MgO and SiO_2 content fluctuated due to the variation of soft grained materials content which has low MgO and high silica and the hard materials which has the opposite content of MgO and SiO_2 (un-weathered boulder).



(a) (b)

Fig. 14. Depth profile chemical composition Ni-Fe-SiO_2-MgO (a) high to medium fractured bedrocks and (b) low to un-fractured bedrocks

The characteristics profile in low to un-fractured (Location B) shows relatively constant depleted upward for MgO and SiO_2 starting from bedrock, lower saprolite, upper saprolite and limonite. This condition is accordance to the actual composition of fracture density within the saprolite zone which is dominated by low to un-fractured rocks.

Ni enrichment zone between two different fractures density area are typically similar on variation. The supergene enrichment for nickel as semi-mobile element is occurred in the saprolite zone through precipitation while magnesia is released from ferro-magnesian minerals due to the travelling down of ground water into the saprolite zone.

The depth profile also still reflected the different thickness of saprolite zone in average that the high to medium fractured area is thicker than the low to un-fractured area.

CONCLUSIONS

Ultramafic complex which is composed by unique peridotite that essentially unserpentinized on west area of Sorowako region has different characteristic due to the variability of fracture density within the bedrocks. The study identified the specific implication of fracture density to the characteristics of saprolitic horizon of nickel laterite deposit in local basis at mined-out sites area that consist of different type of fracture density. The classification of fractures density on bedrocks using one dimension of linear fracture frequency and rock quality designation resulted the different type of two local area of study that the location A is reflected high to medium fractured and location B is low to un-fractured in bedrocks. By the thickness frequency distribution, the area with high to medium fractured has the thickness mode value thicker than the low to un-fractured one. This result is confirming that the fracture density was proven to provide the available opening space in rocks to facilitate the chemical attack during the laterisation.

The opening space in rocks along joints and fractures naturally will be occupied by silica and it is confirming by the characteristics of high-medium fractured area that tend to has higher silica content than the low fractured area. The typical vertical variation of chemical composition also reflected the fracture density composition in rocks especially in lower layer of saprolite zone. For mining purpose, the indication of high silica and low magnesia content (high silica-magnesia ratio) in saprolitic nickel ores should be aware during ore excavation in this area due to the potential silica to dilute the ores.

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