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Local Topographic Model using Position Index for Analyzing the Characteristics of Unserpentinized Lateritic Zones in Sorowako Nickeliferous Laterite Deposit, Indonesia

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***Abstract*— An investigation of the relationship between slope position classification and nickeliferous laterite zones over serpentinized ultramafic terrain in Sorowako, South Sulawesi has been conducted using topographic position index from Light Detection and Ranging data for digital elevation model as references with detail resolution of 5m. The index is calculated by comparing the elevation of each cell in the elevation model to the mean of a specified neighborhood around that cell. The classification has six classes, i.e., valleys, lower slopes, gentle slopes, middle slopes, upper slopes and the local ridges. Chemical properties data from 413 drill holes were used for analysis to confirm the laterite zones –limonite and saprolite. By topographic model, slope position class of local ridges, upper slopes and lower slopes with the slope average of 9.82°, 16.05°, and 14.61° respectively, generally indicated the distribution of thick limonite zones, while saprolite zones were in significantly different pattern due to less or no correlation. 2D semivariogram model for spatial thickness distribution also confirmed the corresponding factor between the significant direction of landform reliefs and limonite thickness. Based on the geochemistry profile of limonite zone, the rate of weathering process in laterite formation is longer than the physical process of removal top profile by erosion or accumulation by transported top materials.**

***Keywords*— nickeliferous laterite zone; serpentinized ultramafic; limonite; saprolite.**

I. INTRODUCTION

Nickel laterite deposits are intensive tropical-style weathering product of underlying ultramafic rocks. The resulting nickel concentration is found within soil horizons and exploitable based on economic sufficiency to be mined and processed. The variability of soil horizons as nickel laterite formation, composition and grades are controlled by lithology, tectonics, climate, and geomorphology. The structure involves the interaction of those variables and consequently profile characteristics are reasonably diverse [1].

Lelong et al. [2] used the term supergene on lateritic ore mineral deposit corresponding to the primary process of evolution that might be defined as weathering which is called for mechanical alteration (e.g., fragmentation) or chemical alteration (e.g., decaying) of earth crust's materials under the influence of atmospheric agents. The weathering acts not only in soil profiles but also in deeper cracks, veins, faults and any porous layers, which are connected to the atmosphere. Some studies related the weathering process, and supergene nickel enrichment has been worked on ultramafic-hosted nickel laterite deposit [1], [3]-[5].

Gleeson et al. [6] described general typical of Ni lateritic profile that has three components from the base profile is parent ultramafic rocks; the second horizon is the initial stages of weathering resulting saprolite as a product and the overlying horizon of upper saprolite as the complete destruction layer with the oxide-rich limonite. Golightly [7] studied particularly case in Sorowako ultramafic complex as part of the vast area of ultramafic massif complex for which a typical nickel ore derived from serpentinized ultramafic rock is commonly characterized by thinner saprolite, many boulders with higher Ni content; while the weathering product of serpentinized ultramafic rocks tends to produce thicker saprolite but lower Ni content.

Many physical and chemical processes including soil erosion and deposition as reflected on the landscape are highly correlated with topographic position, i.e., ridge, valley, flat plain, hill slopes, etc. These physical attributes could be used as the key predictors of favorable landform for potential nickel laterite deposit. The critical study on nickel lateritic weathering characterization related to topographic feature have been made by Ilyas et al. [8] primarily for Ni grade distribution and variation in laterite characterized using geostatistics, topography and paleo-groundwater system.

Nevertheless, there are no similar studies to assess the characteristics of *nickeliferous laterite* zones using the quantitative approach for topographic classification that required for detail investigation in order to prove that these attributes are proper to be used as references to identify the formation of laterite soil.

II. Material And Method

A. Study Area

On a broader view scale, Sorowako is a part of the vast region of East Sulawesi *Ophiolite Belt*, which is located on the *Verbeek* Mountains with locally numerous types of reliefs within the ultramafic terrain. The area lies in near Lake Matano approximately 600 km to the northeastward from Makassar city, South Sulawesi. It is administratively within the East Luwu regency.

As a part of the island of Sulawesi which is tectonically divided into four distinct lithology belts from west to east: (i) the West Sulawesi Tertiary Magmatic Arc and Associated Sediments, (ii) the Central Sulawesi Metamorphic Belt, (iii) the East Sulawesi *Ophiolite* and (iv) accreted continental fragments Banggai-Sula islands and Tukang Besi-Buton platforms [9], [10].

Sorowako ultramafic complex as a part of the East Sulawesi *Ophiolite* is tectonically dismembered with other that exposed in eastern Sulawesi. The outcrops of *peridotite* observed in Sorowako consist mainly of *harzburgite*, *dunite* and minor l*herzolite* and *pyroxenite*. Meanwhile, the East Sulawesi *Ophiolite* in the east of Sulawesi is characterized by dominant *lherzolite* and *harzburgite* with the lense of *dunite*, *pyroxenite*, and *gabbroic* dikes. Most of the rocks are *tectonized* and *serpentinized* [10].

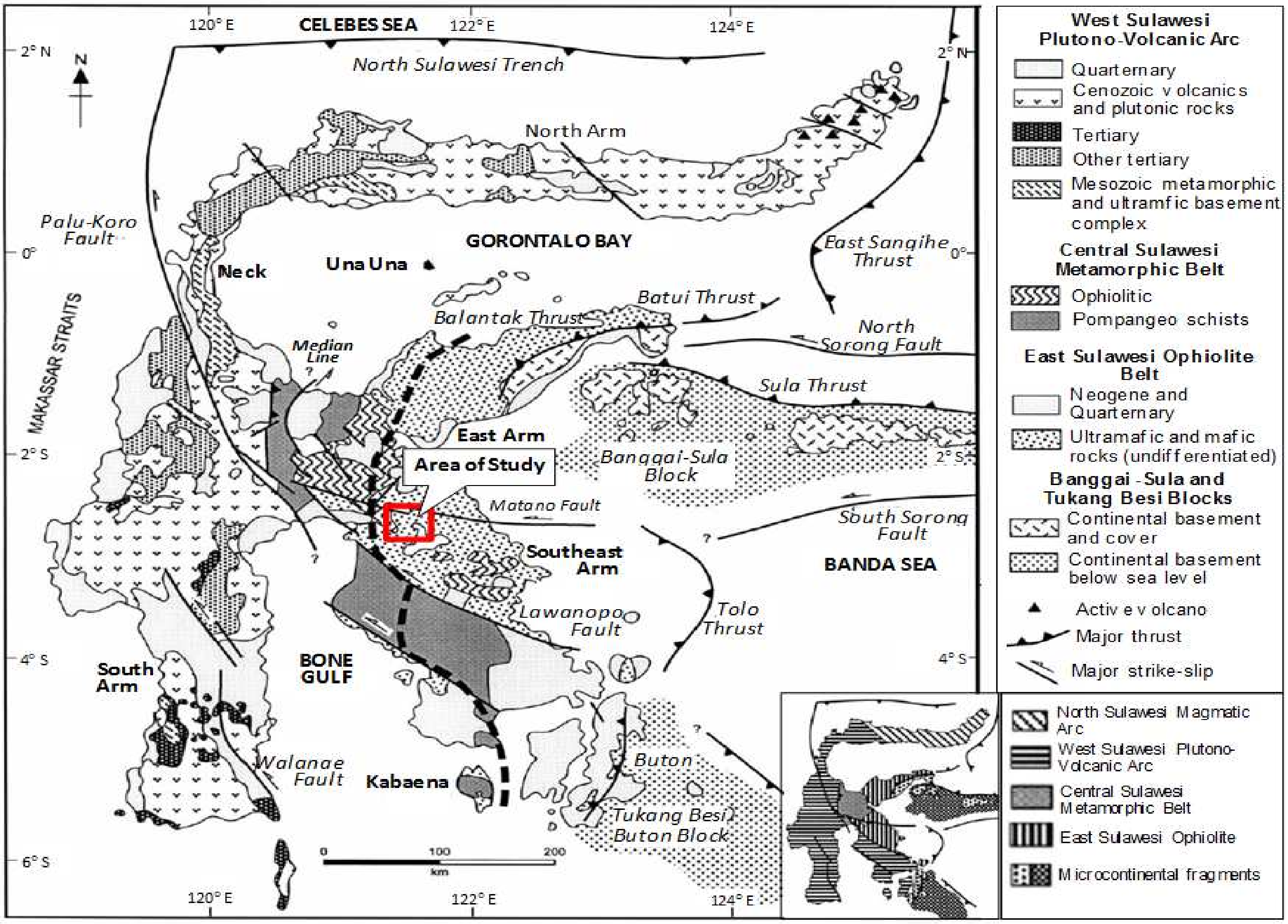

Fig. 1 Regional geology map of Sulawesi with the principle tectonic provinces –inset [9].

The study area focuses on a hilly landform of Sorowako West Block, which is mostly underlying of *serpentinized* ultramafic rock. These typical bedrocks are commonly composed of *peridotite*, which is petrologically dominated by *harzburgitic-peridotite*. The area covered by 105.36 hectares with the range altitude from the lowest of 500 m to the highest of 636.46 m.

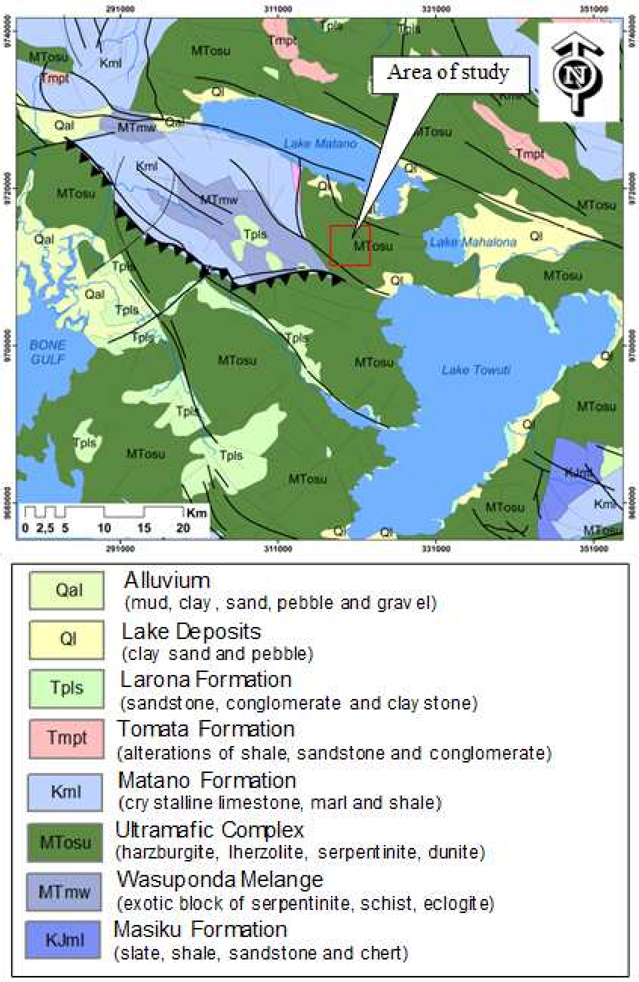

Fig. 2 Local geology of Sorowako and its vicinity[11].

Locally, the surrounding area of study is interconnected with the extreme complexity 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 [12]. The west-northwest trending zone of the *Matano* fault zone has the fault segments that consistently step to the left and are associated with the pull-apart basin on Lake *Matano* along with in-line *grabens* and sags [11]-[13]. The area of study and vicinity as part of Malili Lakes also represent the only hydrologically connected to ancient lake system which composed of three major lakes, *Matano*, *Mahalona* and *Towuti*, and two smaller satellite lakes, *Lantos* and *Masapi*. Lake *Matano* might well be the oldest lake in the system (2- to 4-million years old; based on fault-line displacement), whereas the other lakes are in areas of complex faulting and currently estimated to be <1-million years old (based on sedimentary characteristics) [14].

B. Slope position classification

Topographic model from topographic position index (TPI) was used to perform the slope position classification in this study. The elevation values were taken from Light Detection and Ranging (LiDAR) data for digital elevation model with detail resolution of 5m (Fig 5). TPI is the difference between the elevation at a cell and the average height in a neighborhood surrounding that cell [15]. Positive values represent locations that are higher than the average of their surroundings and conversely for negative values that are the lower ones. The values near zero are either flat areas or areas of constant slope.

The topographic position values provide a powerful means to classify the landscape into morphological classes [16]. The algorithm to calculate TPI value has formulation as follows [17]:

$$TPI_i = Z_0 - \frac{\sum_{1-n} Z_n}{n} \tag{1}$$

Where;

Z_0 = elevation of the model point under evaluation
Z_n = height of the grid within the local window
n = the total number of surrounding points employed in the evaluation

Applied TPI as the basis of the classification system using neighborhood 375m radius to allow small-scale varieties of nested landform and also using the threshold of slope angle for classifying the slope areas within the values near zero. The detail criteria of slope position classes are described in Table 1.

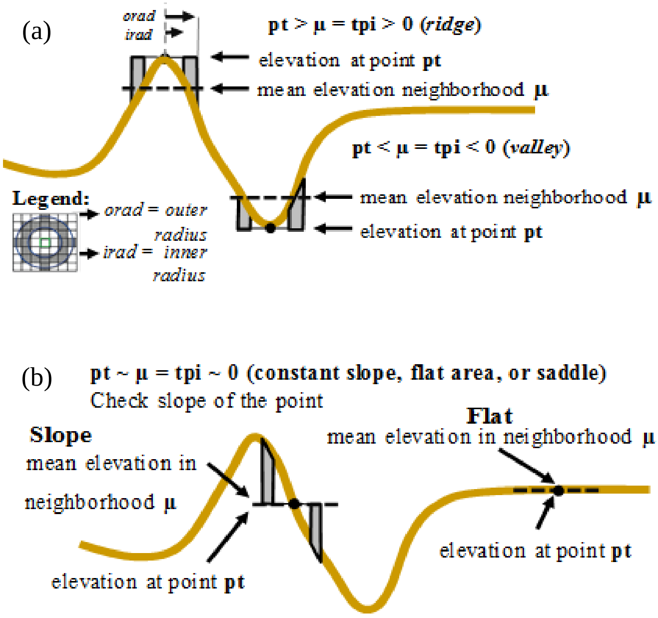

Fig. 3 Illustration for calculating topographic position index[15]

TABLE I
SLOPE CLASSIFICATION BASED ON STANDARDIZED TPI[18]

Slope Classes	**Description**
Valley	tpi ≤ -1
Lower Slope	-1 < tpi ≤ -0.5
Gentle Slope	-0.5 < tpi ≤ 0.5; Slope ≤ 5°
Middle Slope	-0.5 < tpi ≤ 0.5; Slope > 5°
Upper Slope	-0.5 < tpi ≤ 1
Ridge	tpi > 1

C. Boreholes data and domain analysis

All boreholes as the input data were mainly provided by PT Vale Indonesia that consists of 413 boreholes drilled in the area of study with regular configuration spacing on 50m lying on all landform classes. For each borehole, analyses of major and minor elements using X-ray fluorescence method are available for all drilling intercepts with cumulative of 15,703 samples. The critical point that needs to be noted in this study is related to the mean value as correspondence of chemical analyses which measured on 1m compositing interval for each laterite geological domain. The focus for major and minor elements are limited to the Ni, Fe, SiO_2, MgO, Cr and Al in percentage by weight.

Domain analysis for lateritic geological layer modeling was evaluated based on depth profile of major and minor elements for each intercept. Well-understanding of basic geological concept on chemical weathering product of nickel laterite deposit is the most important part to define the geological domain. The complete profile on nickel laterite deposits consist of three geological layers: *limonite*, *saprolite*, and bedrock (see Fig. 4). The contact between each geological layer reflected a boundary with the sharp increasing or decreasing trend in chemistry composition from top to bottom (see Fig 6). Iron as non-mobile element strongly increased from the bottom profile and reached its maximum value on the top layer as residual concentration.

In contrast, MgO and SiO_2 as mobile elements are depleted from bottom to top of profiles with the strong trend as an indication of chemical leaching out process. Ni as the semi-mobile element is concentrated in the lower part through supergene enrichment and leached out of the upper part of the laterite profile.

Fig. 4 Outcrop of typical laterite profile over *serpentinized* ultramafic rock

Minor elements composition that also could be used as the active reference for domain determination is Cr and Al. Chrome as chromite in weathering profile of ultramafic rocks shows increasing from bottom to top profile. Chromite exists in limonite and insoluble in groundwater as stated in very stable condition. Alas, a non-mobile element in laterite profile is soluble in acid or alkaline condition. Groundwater mostly present on balance condition range (pH 4.5-9.5) where alumina found and form clay minerals as a result of decomposition of ferromagnesian minerals. This process is a part of excellent chemical weathering and leaching that make the behavior of Al is increasing upward in the profile. Based on the result from domain analysis, the thickness data of weathering product for each borehole was generated (Table 2).

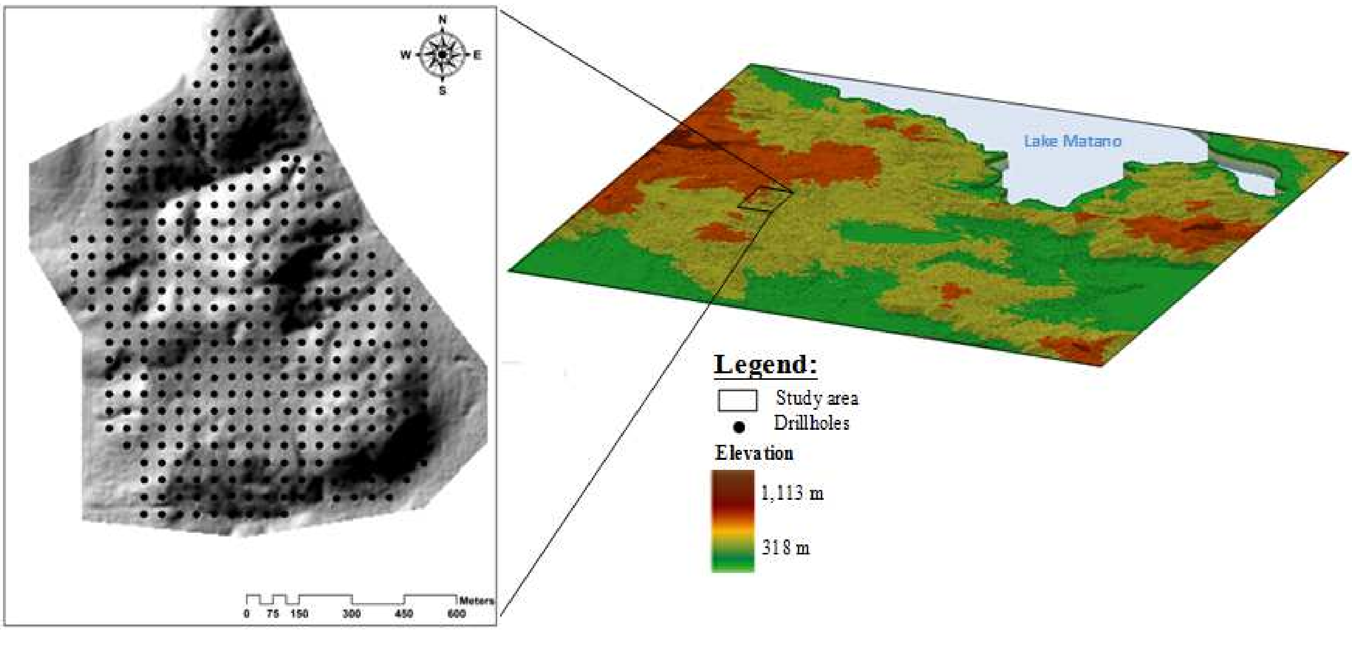

Fig. 5 Topography of ultramafic terrain in Sorowako including study area which supported by 50m drill spacing

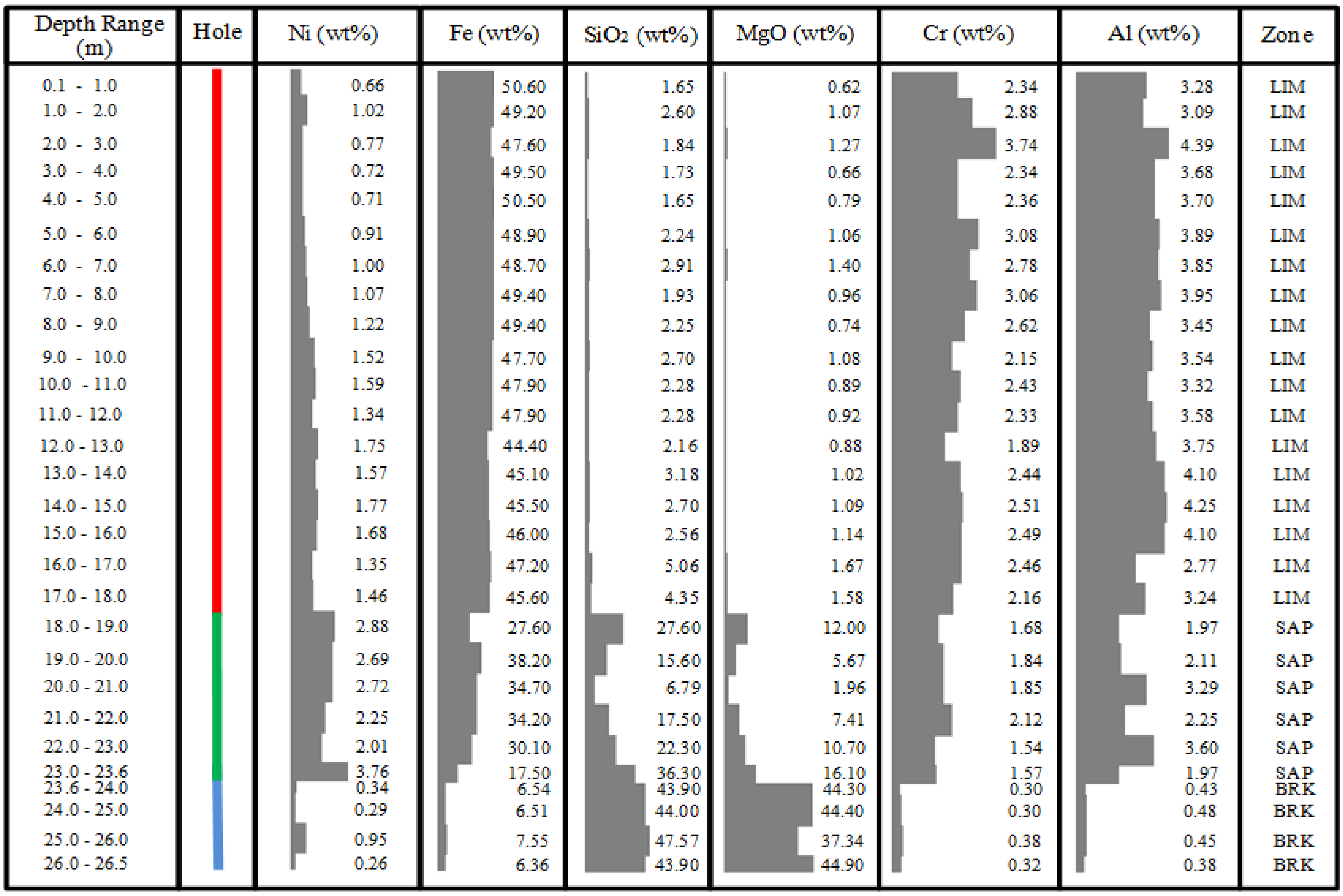

Fig. 6 Block histogram depth profile of Ni, Fe, SiO2, MgO, Cr and Al from borehole data intercepts as references for domain analysis

TABLE II
SUMMARY STATISTIC OF THICKNESS DATA SET

Properties	Zone	N	the Min	Max	Mean	St. Dev.
Top Elev.	Lim	409	435.35	554.89	506.7	29.55
	Sap	393	419.35	548.68	484.0	28.16
Bot. Elev.	Lim	409	419.43	548.67	493.0	28.34
	Sap	393	406.43	539.66	484.1	28.15
Thickness	Lim	409	0.30	37.00	14.7	8.08
	Sap	393	0.20	43.00	8.9	6.39

III. RESULTS AND DISCUSSION

A. *Slope position category on the lateritic landscape*

Topographic position index (TPI) as the reference value to determine landscape category was applied to generate a topographic model of the study area. Class distribution of slope position on, a local basis was identified spatially. The classification has six slope classes, i.e., local ridges, upper slopes, middle slopes, lower slopes, gentle slopes and valleys (Fig. 7). Based on the observed class distribution, the largest slope class in the study area is intermediate slopes, while the smallest is gentle slopes.

Geometrically, the complete nickel laterite profiles are possibly present on all category of slope position with the local thickness varieties. The thick limonite zones are mostly found on the class of local ridges, upper slopes, and lower slopes. Those landforms have the slope average of 9.82°, 16.05°, and 14.61° respectively. Meanwhile, the thick *saprolite* zones are found on the class of gentle slopes and middle slopes with the average gradient of 19.72° and 18.34° respectively. A noted point was made for a gentle slope that only covering 1.02% of the study area, which is possibly, not represented the reality of data statistically. The critical position on the typical thickness of laterite profile related to topography and the rate of chemical weathering is balancing condition between the forming of new laterite product at the base profile and the eroded surface of mature laterite at the top of the pattern. As a soil, the main elements of topography, i.e., elevation, slope, and aspect can influence the development of laterite product. The topographic condition on stable landform directly affects the environmental features such as soil properties and genesis [19]. Spatial distribution of interpolated thickness variability along the ridge and valley are shown in Fig 8.

TABLE III
DESCRIPTIVE STATISTICS OF CATEGORICAL VARIABLES IN STUDY AREA OVER ULTRAMAFIC TERRAIN OF SOROWAKO

Category	Variable	% of area	Thick Lim		Thick Sap	
			Mean	S.D.	Mean	S.D.
Slope position	Valley	7.32	13.72	5.06	5.82	4.80
	Lower Slope	19.53	15.04	9.06	8.08	5.53
	Gentle Slope	1.02	14.11	6.72	9.80	5.58
	Middle Slope	35.34	13.14	8.16	9.58	7.49
	Upper Slope	18.33	15.99	8.35	8.52	6.77
	Ridge	18.46	16.22	8.46	8.32	5.70

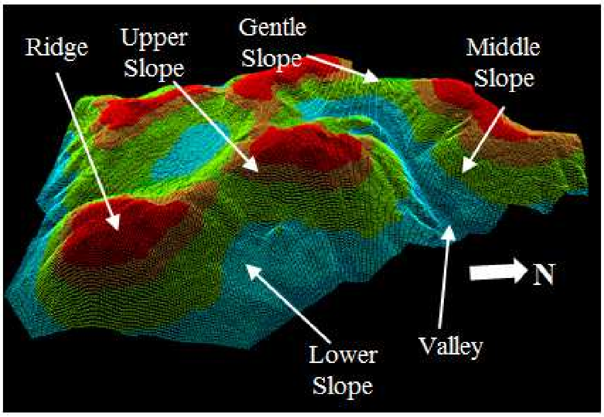

Fig. 7 Class distribution of slope position in the study area (exaggeration z=2)

Correlation between slope position category and thickness zone was examined by evaluating a coefficient of determination (R^2). Clearly, the correlation between topographic slope angle and layer thickness for limonite zone is significantly different with *saprolite* zone (see Fig. 9 and 10). The relationships against limonite indicate moderate negative correlation, while the *saprolite* zones are absent. The R^2 value for limonite zone (R^2=0.21) is higher than *saprolite* (R^2=0.00). Based on this result, it can be interpreted that the topographic slope angle played more significantly to control the weathering depth of limonite zone than *saprolite*. Limonite zone as a top layer in laterite soil profile will be more sensitive to the elevation that affects to the physical and chemical characteristics spatially. Decomposition process in the top tier of laterite product is controlled by temperature where the higher slope class with low heat will have lower fertility than the lower slope position [20].

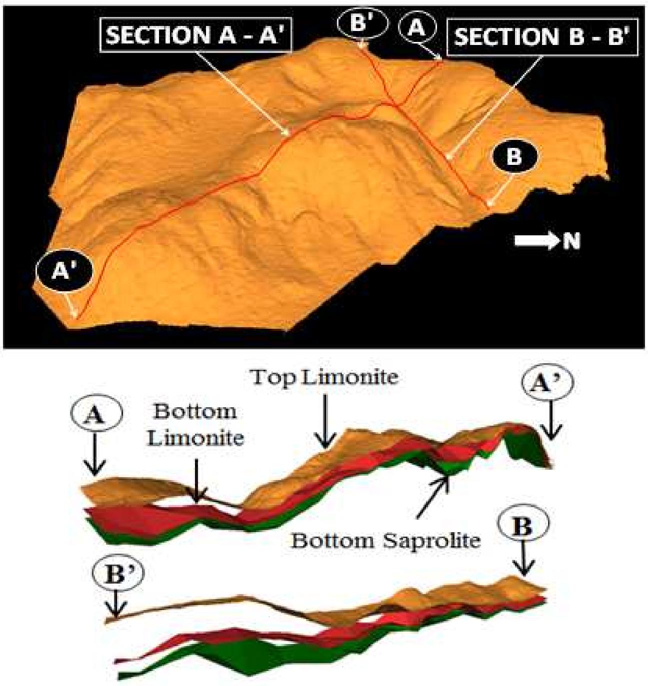

Fig. 8 Spatial distribution of interpolated layer thickness from the borehole dataset which represented surface topographic condition (exaggeration z=2)

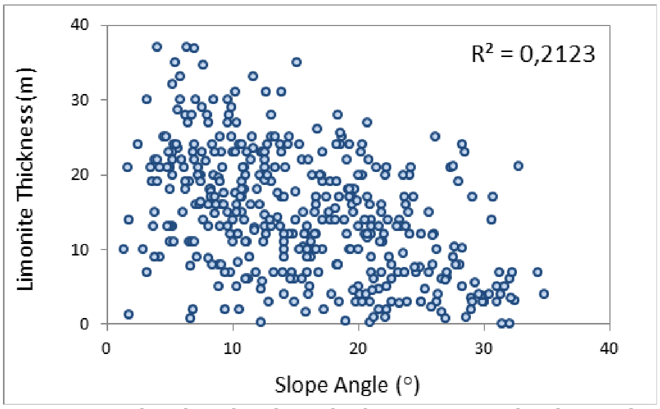

Fig. 9 Scatterplots show the relationship between topographic slope angle and limonite thickness

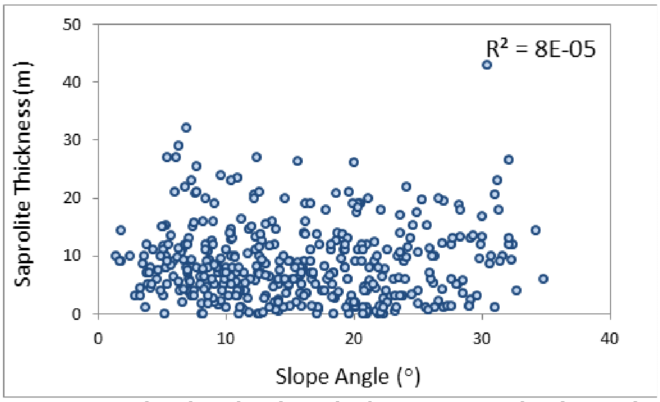

Fig. 10 Scatterplots show the relationship between topographic slope angle and *saprolite* thickness

B. 2D model for lateral distribution

A surface topographic corresponding to the laterite horizons was modeled using borehole data. The thick limonite zone with thickness more than 20m mostly covered along ridges on high topographic relief and some of them are found at lower ones as depression zone. Distribution of the thick limonite zones in the study area is shown in Fig. 11.

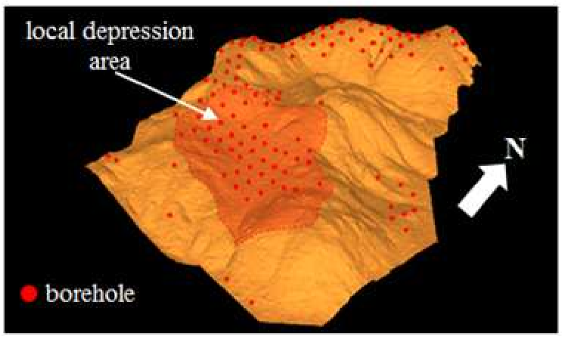

Fig. 11 Detail 3D surface model with the thick limonite distribution, showing local depression area (exaggeration z=2)

Variogram map as the 2D variography model using limonite thickness data indicates the trend of regional spatial distribution which corresponding to the significant N105E axis of high topographic and depression zone (see Fig 12). Local ridges and upper slopes category dominates high topographic reliefs. Meanwhile, the good preserved and proper formation of limonite zone on the average slope focused on depression area due to the possibility of poor drainage, low water run-off, and high water absorption. The variography of limonite thickness exhibits geometric anisotropy with profound nugget effect (3.6% of a sill of 100%), and two nested spherical structures were fitted to the experimental data.

2D cartography of *saprolite* thickness reflects the absent correlation with slope surface angle. The trend of significant axis for local spatial distribution is significantly differenced with the regional contour of the topographic model. The *variogram* map of *saprolite* thickness shows the local major NE-SW axis. The variography of *saprolite* thickness also exhibits geometric anisotropy with nugget effect 10% of 100% sill. Two nested spherical structures were also modeled for the in-situ *saprolite* data (Fig. 13). This cartographic model is confirming that topographic factor has a minimum contribution to the formation of *saprolite* layer. Fracture density on ultramafic bedrocks played the critical roles during laterisation, and each fractures density type implies the *saprolite* zones.

C. Geochemistry profile analysis

Most of boreholes data penetrate into three main horizons of nickel laterite (lim, sap, and brk). The different category of slope position also correlates with the depth profile. The vertical depth geochemical compositions for each group were examined to understand the characteristic of elements chemical mobility. Although the slope position category as represented to physical properties and the geochemistry profile is the product of chemical weathering, the comparison between the depths profile within the low rate of removal soil area and the high rate one still being reflected by major and minor elements composition on depth profile especially on limonite zone.

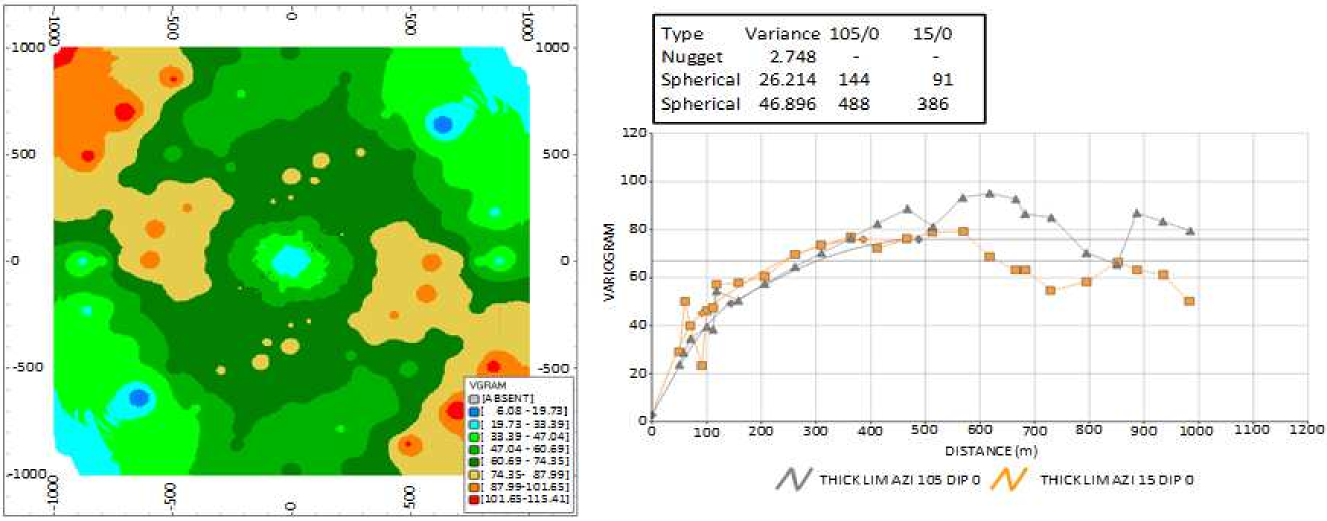

Fig. 12 Variogram map of limonite thickness and semivariogram model along two directions

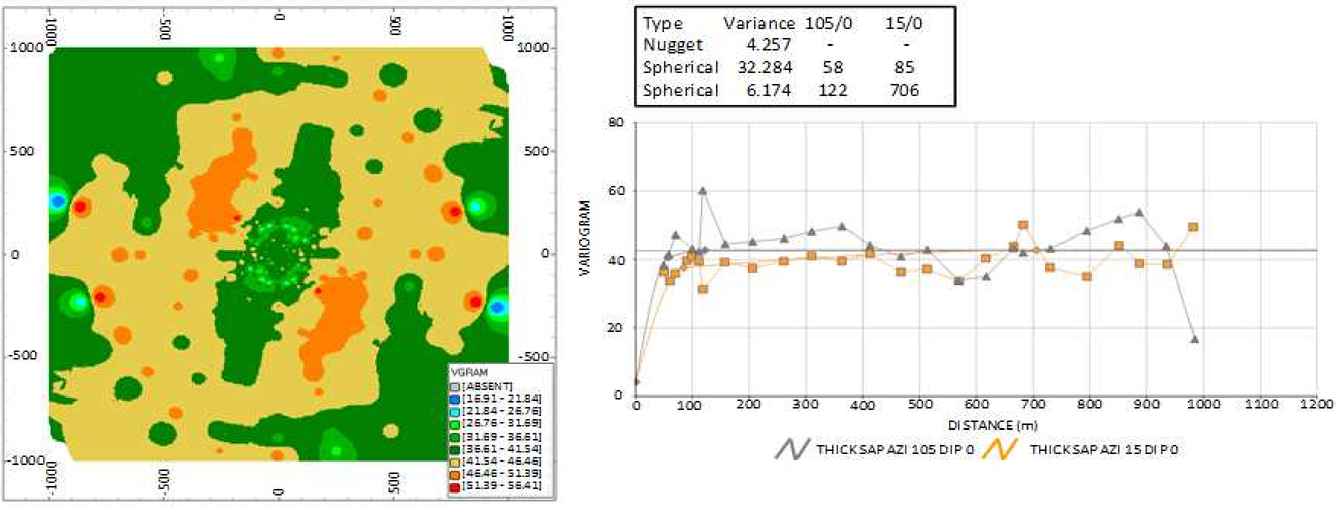

Fig. 13 Variogram map of *saprolite* thickness and semivariogram model along two directions

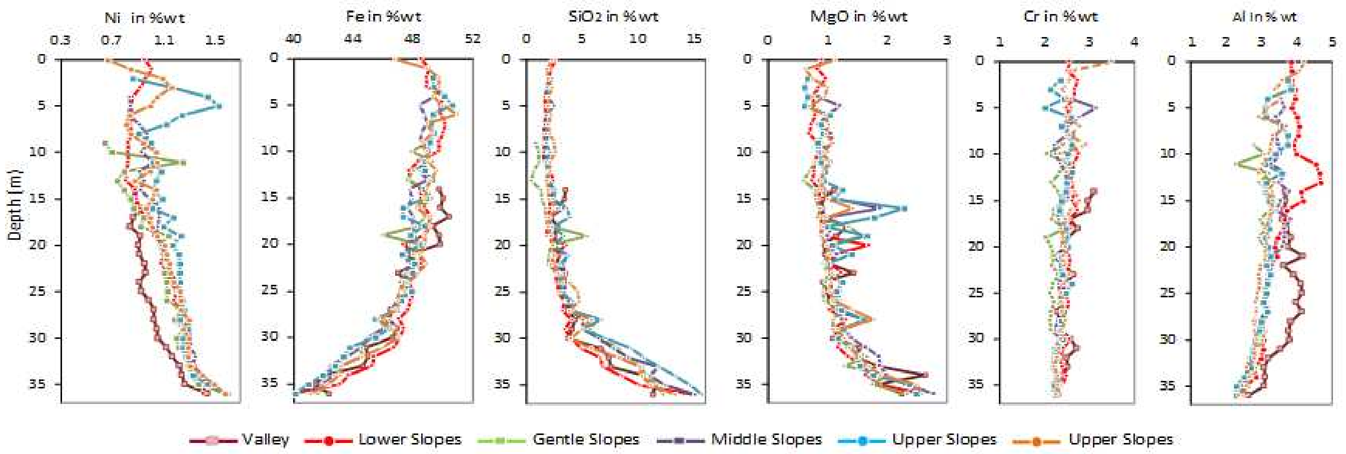

Fig. 14 Composition of Ni, Fe, SiO_2, MgO, Cr and Al on limonite profile for each slope position category

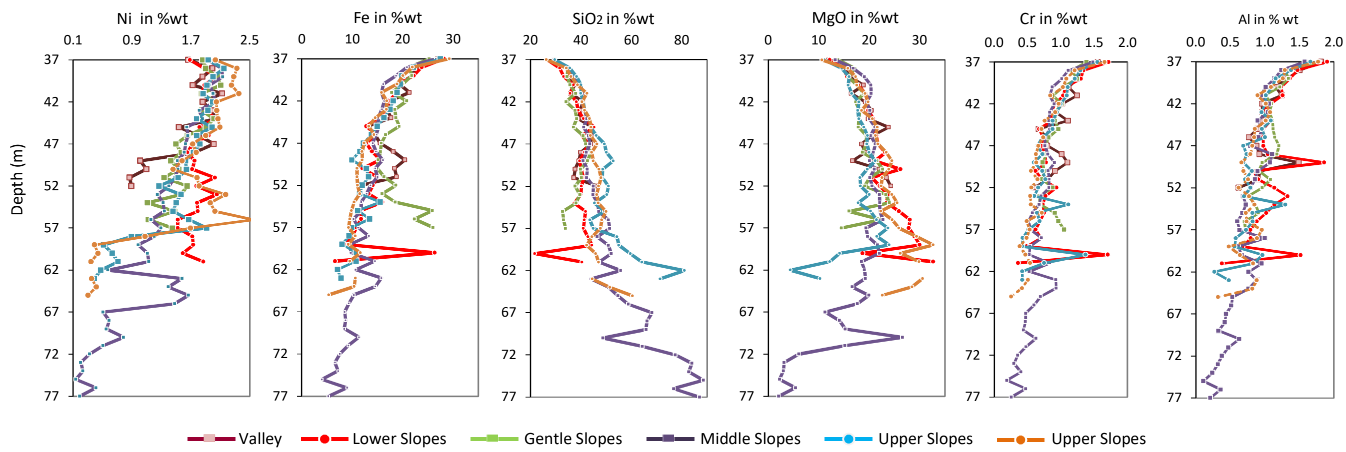

Fig. 15 Composition of Ni, Fe, SiO2, MgO, Cr and Al on saprolite profile for each slope position category

Geochemical depth-compositions of limonite profile for each slope position category are studied in detail; all, which shows similar chemical variations (see Fig 14). From the dataset, it is understood that Fe is strongly increased from the lower limonite to top profile. The slope position area with high rate removal soil has thin of high Fe content on its top profile which characterized by red-brown materials and disappearance of original textures.

Based on the mineralogy, the hematite as a primary mineral, which associated with goethite, is on thinner thickness comparing to the area with low rate removal soil. The presence of hematite in solid residues of the *serpentinized* ultramafic-hosted domain is likely the result of iron precipitation derived from goethite dissolution [21]. The lower profile of the limonite zone, which consists of mostly decomposed silicate, which is transforming into goethite, shows the similar depth thickness for all area categories.

In contrast, SiO_2 and MgO are strongly depleted from the lower part to top profile of limonite zone. The composition shows that the silica and magnesium have leached out from the top of the pattern. The increased proportion of goethitic materials in lower part possibly maintains a certain degree of original rock texture.

The concentration of Cr and Al show increasing upward from lower limonite. The behavior of Cr and Al in weathering profile generally indicates a positive correlation with Fe. The correlation behaviors are indicating the immobility of these elements at weathering profiles. Chromium in the spinel group (chromite or magnetite) was relatively resistant to acid through the reaction takes on an extended period. Aluminum in limonite might be alternatively replaced for Fe in goethite structures Although Ni in general shows supergene behavior, in limonite zone, it shows strong positive correlation with Fe. The ratio of Fe to Ni is mostly increasing upward from the lower part to top profile. Concentration factors of Ni on residual soil/limonite generally similar for all slope position categories with a factor of 2.

By comparing the geochemical depth-composition of limonite zone for each slope position category, the influence of topographic relief features on the laterite development is identified. On valley and average slope which dominated with a range of medium to steep slopes, only a little rainwater absorption into the profile and much of rainwater runoff. The condition promotes the high rate removal any residual accumulation on top limonite profile. The residual laterite on a local ridge, upper slope, gentle slope and the lower slope is still survived due to the rate of residual accumulation exceed their natural erosion. The profile also indicated that the price of the weathering process is longer than the physical process of removal top profile by erosion or accretion by trans, ported materials.

Geochemistry depth profile of *saprolite* zone, which has no correlation on layer thickness with topographic slope angle shows normal nickel laterite behavior both major and minor elements composition (Fig 15). The different thicknesses and elements composition between each area even for each hole in this study are more affected by rock fracture system that characterized based on their fracture density. The system has the impact especially in the enhancement of Ni grade because of the preferential pathways were formed by the method for dissolved Ni transportation and ultimately precipitation.

IV. Conclusion

The results of this research proved that the topographic model using position index for slope classification could be performed to investigate the characteristics of nickel laterite zones over the host-type of *serpentinized* ultramafic rock at Sorowako, South Sulawesi. By local topographic model, the area of study has six classes, i.e., the valleys, lower slopes, gentle slopes, middle slopes, upper slopes and local ridges. The quality of local hills, high hills and lower slopes with the slope average of 9.82°, 16.05°, and 14.61° respectively, generally indicated the distribution of thick limonite zones, while *saprolite* zones were in significantly different pattern due to less or no correlation. Coefficient determination value between slope angle and layer thickness for limonite zone is higher than *saprolite*. These can be interpreted that the topographic condition has played more significantly to control weathering depth of limonite zone than *saprolite*.

Two-dimensional cartographic model of limonite thickness also shows the corresponding spatial distribution with topographic features which reflected by the direction of the major axis that parallels along the primary route of local ridges, upper slopes, and lower slopes. The depression area only influences a local range of limonite thickness variance. Meanwhile, the spatial distribution of *saprolite* thickness using two-dimensional variographic model has potentially difference on significant axis direction with landform reliefs that confirmed the minor contribution factor of topographic features on the formation of *saprolite* zones.

The implication of topographic features can also be identified by geochemical depth-composition of limonite zone for each slope category. On valley category, apparently that the layer with high Fe content on its top profile which characterized by red-brown material are thinners than ridges, upper slopes, and lower slopes category. These characteristics are the impact of their high rate of removal on residual accumulation, which is promoted by high water runoff on their surface. Geochemical depth-composition of *saprolite* zone shows the similar chemical variation of normal laterite behavior. The difference on their bottom profile between each area is more affected by rock fracture system that characterized based on their fracture density.

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