Study on Sc-bearing Lateritic Ni deposits in Ultramafic Rock from Sulawesi: A New Paradigm in Indonesia Metal Mining Industry

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Abstract. Scandium (Sc) and its compounds are used in many modern-technology applications such as in optical, electronic, aeronautical, and fuel-cell industries. However, Sc occurrence were only limited in a very specific area with limited deposit and little attention has been paid to the genesis of Sc-bearing deposits in the world. 6 (six) bedrock samples and 15 (fifteen) lateritic samples (saprolite to limonite) were collected and studied to investigate the distribution of Sc grades in lateritic Ni deposits and identify Sc-bearing minerals in laterites from ultramafic rocks in West Blok, East Block and Petea prospect in Soroako, South Sulawesi, Indonesia. The study suggests that scandium is enriched in limonite layer in weathering profile. In general, pyroxene bearing rich bedrock (harzburgite in composition) will contain higher Sc content in their weathering product. It is suggested that the Sc are associated with the occurrence of iron oxide from pyroxene. However, as the occurrence of Sc is very limited, the most promising result was shown by East Block profile in which the enrichment of Sc is also supported by enrichment of NiO content. Sc will be viable as by-product of nickel laterite.

1. Introduction
Scandium (Sc) is an important metal for various applications in globalization era and has been considered as one of the critical metals [1]. Scandium and its compounds have been found wider applications such as in optical, electronic, aeronautical, and fuel-cell industries [1-4]. The properties of Sc-strengthened alloys and Sc2O3-stabilised ZrO2 materials are particularly promising. The Al–Sc alloys (0.35–0.4% Sc) have a number of superior properties including light weight, high strength, good thermal resistance and long durability [5]. The principal applications of the Al–Sc alloys were for sporting equipment and military demand [3]. For example, scandium alloys were applied in premium bicycle frames and in fighters and missiles. The application of Mg–Sc alloy to aircraft engines could save electricity and energy consumption [1, 6]. Scandia-stabilized zirconia has extremely high oxygen-ion conductivity for use as a high efficiency electrolyte in solid oxide fuel cells [1, 7].

New report suggests that Sc3+ enriched in mafic minerals such as pyroxene, amphibole and magnetite and poor in olivine [1]. These typical minerals are found in mafic to ultramafic rocks. Based on the most update investigation, scandium can be extracted from weathering crust of highly weathered nickel-contained ultramafic rock which is called as lateritic deposit. Scandium will be concentrated in limonite and saprolite layer, but the volume of enrichment is still unknown. Sulawesi Island is one of the islands where lateritic deposits from heavily weathered ultramafic are widely
distributed [8]. Currently, some mining companies extracted nickel ore from the lateritic deposit from ultramafic rocks, particularly from the olivine-rich parent rocks. However, the Sc occurrence and distribution in this deposit have not been studied in detail. The lateritic soil of the ultramafic rocks can be potential source of scandium. In this study, we investigate the distribution Sc grades of lateritic Ni deposits and identify Sc-bearing minerals (they may be amorphous materials) in laterites in ultramafic rocks from Indonesia, particularly in Sulawesi as one of the Sc-bearing deposits. As the price of Sc ore is significantly expensive along with demand, Sc will be a new target to intensify the mining exploration process.

2. Regional Geology

Sulawesi consists of four major litho-tectonic units comprising the Eastern, Northern and Western Sulawesi Provinces and the Banggai-Sula Microcontinent (Figure 1). Following is the regional geology of Sulawesi based on [8] and references there in. The Western Sulawesi Province is divided into three parts based on geomorphological and geological criteria, viz. Southwest (SW), Central West (CW), and Northwest (NW) Sulawesi. SW Sulawesi is different from the others being less tectonically deformed and less mountainous, and lacking CAK-type igneous rocks. As discussed by [8, 9] the Eastern Sulawesi Province consists of several quasi-concentric arcuate belts, which are composed of, from west to east: 1) sheared metamorphic rocks commonly referred to as the Central Sulawesi Metamorphic Belt; 2) a highly tectonized mélange of ophiolitic, metamorphic, and Mesozoic-Paleogene sedimentary rocks, and 3) predominantly ophiolite rocks. A fourth zone, consisting of imbricated Mesozoic and Paleogene rocks that fringes the southeast margin of the East Arm, belongs to the Banggai-Sula Province and marks the Neogene collision zone between the Banggai-Sula continental fragment and the ophiolite terrane. These four zones are unconformably overlain by syn-to post-orogenic sedimentary deposits (“Celebes Molasse”).

The Northern Sulawesi Province occupies a large part of the North Arm. The E-W part of this arm is made up of Cenozoic arc volcanic and plutonic rocks and associated sedimentary rocks. The NE-trending part of the north arm is largely covered by Pliocene to recent volcanic rocks. The Banggai-Sula and Tukang Besi Continental Fragments are located in the eastern and southeastern parts of Sulawesi, respectively. The Bangai-Sula microcontinent is represented above sea level by a group of islands, including Peleng, Banggai, Taliabu and Mangole Islands whereas the Tukang Besi microcontinent comprises Buton, Muna and surrounding smaller islands. The mafic-ultramafic sequences formed ophiolite complex which are widely distributed in eastern Sulawesi Province (especially in Soroako area) (Figure 2) and small outliers in western Sulawesi Province (Bantimala and Barru areas). These complexes have been variously interpreted as members of ophiolites from different tectonic settings.

Figure 1. Regional geology of Sulawesi [8, 10]
3. Methodology
The weathered ultramafic (lateritic) were analyzed for concentration of major elements using an X-ray fluorescence spectrometer (XRF) method in AIST Laboratory in Tsukuba and Department of Earth Resources Engineering, respectively. Rare earth element and trace element composition for both samples groups were determined by the ICP-MS method in Actlab, Canada. Mineral chemistry analysis will be conducted by electron microprobe analysis (EMPA) method using JEOL JXA-8530M in AIST laboratory in Tsukuba Japan as our international collaboration institution.

4. Result and Discussion
4.1. Sample description
We collected 6 bedrock samples and 15 lateritic samples (saprolite to limonite) from ultramafic rocks in West Blok, East Block and Petea prospect in Soroako. The bedrocks consist of peridotite or harzburgite (East Block), dunite (West Block) and Serpentinite (Petea). Weathering profile in Soroako showed a typical of lateritic profile consists of bedrock, saprolite, limonite and overburden as shown in Figure 3.
serpentine. Associated magnetite is presumed to be a by-product of serpentinization. A dunite (22-2 BR) is show low to moderate serpentinization in West Block (Figure 5). Olivine occurs as main minerals and made up 90–95% of the rock. Orthopyroxene show a distinct extinction and partly replaced by chlorite. Chromite abundance is 3–5%; it usually forms small grains 0.2–1 mm in size. Serpentinite (21-4 BR) shows a mesh texture and in places partially pseudomorphs olivine and orthopyroxene, along with spinel grains. The absence of evidence for clinopyroxene implies that it is a highly altered harzburgite. The serpentine is admixed with small amounts of chlorite. Individual serpentine pseudomorphs are generally fine-grained, with randomly oriented fibrous texture (Figure 6).

![Figure 4. Outcrop of peridotite (harzburgite) bedrock in East Block](image)

4.2. *Geochemistry of Sc in weathering profile*

Results of chemical analyses for peridotite are described in Table 1. The bedrock in Petea profile contains of 40.8 wt% SiO$_2$, 34.8 wt% of MgO, 8.7 wt% Fe$_2$O$_3$, 0.2 wt% Ni, 9.8 ppm Sc (Figure 7). In relation to this, the weathering profile show decreasing content of SiO$_2$ and MgO, and increasing trend of Fe$_2$O$_3$ and Sc. SiO$_2$/MgO ratio shows a slightly increasing trend from bedrock to soft saprolite but significantly enriched in yellow limonite layer.

Overall, West Block weathering profiles showing a somewhat similar pattern to Petea profile. SiO$_2$ and MgO are significantly decreased whereas Fe$_2$O$_3$, Sc and SiO$_2$/MgO ratio are enriched. This variation suggests the enrichment of Sc was concentrated in the limonite horizon.

Weathering profile of East Block also displays a similar trend in which SiO$_2$ and MgO are significantly depleted. Fe$_2$O$_3$ and Sc are enriched toward the upper part of the weathering profile whereas SiO$_2$/MgO ratio shows an extreme enrichment in yellow limonite, similar to Petea profile (Figure 8). These finding suggests that scandium is enriched in limonite layer in weathering profile from ultramafic rocks in Soroako.

![Figure 5. Heavily jointed dunite outcrop in West Block](image)
It is also interesting to note that generally pyroxene bearing rich bedrock (harzburgite in composition) contain higher Sc content in their weathering product. The enrichment of Sc in limonitic layer is in a good agreement with the result of study in Eastern Australian [1]. The study suggests that scandium is enriched in limonite layer in weathering profile from ultramafic rocks in Soroako. In general, pyroxene bearing rich bedrock (harzburgite in composition) will contain higher Sc content in their weathering product. It is suggested that the Sc are associated with the occurrence of iron oxide from pyroxene. However, as the occurrence of Sc is very limited, the most promising result was shown by East Block profile in which the enrichment of Sc is also supported by enrichment of NiO content. Sc will be viable as by-product of nickel laterite.

### Table 1. Geochemical composition of bedrock, saprolite and limonite

| Sample name | Rocktype | Deposit          | SiO2 (%) | Fe2O3 (T) (%) | MnO (%) | MgO (%) | NiO (%) | Co (%) | Sc (%) | SiO2/MgO ppm | % |
|------------|----------|------------------|----------|---------------|---------|---------|---------|--------|-------|--------------|---|
| 140621-1RL| Red limonite | Petea (A)        | 3.16     | 50.09         | 0.06    | 0.7     | 0.83    | 0      | 82    | 4.514286     |   |
| 140621-1YL| Yellow limonite | Petea (A)     | 27.86    | 43.7          | 0.08    | 1.18    | 0.75    | 0      | 85    | 23.61017     |   |
| 140621-15S| Soft saprolite | Petea (A)    | 36.32    | 26.55         | 0.98    | 17.3    | 1.55    | 0.1    | 32    | 2.096998     |   |
| 140621-1HS| Hard saprolite | Petea (A)   | 39.35    | 16.35         | 0.65    | 26.5    | 1.65    | 0      | 16    | 1.482668     |   |
| 140621-1BR| Bed rock (harzburgite) | Petea (A) | 40.818   | 8.773         | 0.21    | 34.8    | 0.2     | 9.8    | 1.171954 |     |

| Sample name | Rocktype | Deposit | SiO2 (%) | Fe2O3 (T) (%) | MnO (%) | MgO (%) | NiO (%) | Co (%) | Sc (%) | SiO2/MgO ppm | % |
|------------|----------|---------|----------|---------------|---------|---------|---------|--------|-------|--------------|---|
| 140621-2RL| Red limonite | Petea (B) | 7.35     | 62.47         | 0.59    | 1.54    | 0.86    | 0.1    | 83    | 4.772727     |   |
| 140621-2YL| Yellow limonite | Petea (B) | 20.74    | 45.29        | 0.73    | 10.6    | 1       | 0.1    | 58    | 1.965877     |   |
| 140621-2SS| Soft saprolite | Petea (B) | 32.15    | 35.73        | 0.49    | 10.8    | 1.29    | 0      | 48    | 2.987918     |   |
| 140621-2BR| Bed rock (harzburgite) | Petea (B) | 38.703   | 8.543         | 0.09    | 39.9    | 0.22    | 7.1    | 0.971168 |    |

| Sample name | Rocktype | Deposit | SiO2 (%) | Fe2O3 (T) (%) | MnO (%) | MgO (%) | NiO (%) | Co (%) | Sc (%) | SiO2/MgO ppm | % |
|------------|----------|---------|----------|---------------|---------|---------|---------|--------|-------|--------------|---|
| 140621-3RL| Red limonite | East Block | 12.82   | 47.41         | 0.96    | 4.97    | 1.77    | 0.1    | 72    | 2.579477     |   |
| 140621-3YL| Yellow limonite | East Block | 39.35   | 45.67        | 0.65    | 0.83    | 1.03    | 0.1    | 40    | 47.40964     |   |
| 140621-3SS| Soft saprolite | East Block | 34.46   | 18.63        | 0.25    | 27.6    | 3.6     | 0      | 20    | 1.249003     |   |
| 140621-3BR| Bed rock (peridotite) | East Block | 39.21  | 9.054         | 0.1     | 40.6    | 0.22    | 8      | 0.966692 |   |
| 140621-4BR| Bed rock (peridotite) | East Block | 42.999  | 10.047       | 0.11    | 44.1    | 0.24    | 9.3    | 0.975676 |   |
| Sample name | Rocktype                  | Deposit   | SiO₂ (%) | Fe₂O₃ (T) (%) | MnO (%) | MgO (%) | NiO (%) | Co (%) | Sc ppm | SiO₂/MgO % |
|-------------|---------------------------|-----------|----------|---------------|---------|---------|---------|-------|--------|------------|
| 140622-1RL  | Red limonite              | West Block| 1.82     | 69.84         | 0.55    | 0.82    | 1.26    | 0.1   | 87     | 2.219512   |
| 140622-1YL  | Yellow limonite           | West Block| 3.42     | 66.9          | 1.38    | 1.45    | 0.83    | 0.2   | 71     | 2.358621   |
| 140622-1SS  | Soft saprolite            | West Block| 58.35    | 16.42         | 0.07    | 12.5    | 2.57    | 0     | 19     | 4.686747   |
| 140622-1BR  | Bed rock (dunite)         | West Block| 42.439   | 9.746         | 0.1     | 44.8    | 0.25    | 9.4   | 0.948273|

| Sample name | Rocktype                  | Deposit   | SiO₂ (%) | Fe₂O₃ (T) (%) | MnO (%) | MgO (%) | NiO (%) | Co (%) | Sc ppm | SiO₂/MgO % |
|-------------|---------------------------|-----------|----------|---------------|---------|---------|---------|-------|--------|------------|
| 140622-2RL  | Red limonite              | West Block| 2.62     | 75.02         | 1.57    | 0.83    | 1.53    | 0     | 40     | 3.156627   |
| 140622-2SS  | Soft saprolite            | West Block| 43.15    | 16.85         | 0.2     | 30.3    | 1.61    | 0     | 7      | 1.424092   |
| 140622-2BR  | Bed rock (dunite)         | West Block| 42.386   | 9.735         | 0.1     | 44.9    | 0.23    | 8.4   | 0.944893|

**Figure 7.** Diagram showing vertical distribution of some elements in Petea A

**Figure 8.** Diagram showing vertical distribution of some elements in East Block
5. Conclusions

- Scandium is enriched in limonite layer in weathering profile from ultramafic rocks in Soroako.
- Pyroxene bearing rich bedrock (harzburgite in composition) will contain higher Sc content in their weathering product.
- Sc are associated with the occurrence of iron oxide from pyroxene and will be viable as by-product of nickel laterite.

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References

[1] Chasse, M., Griffin, W.L., O’Reilly, S.Y., Calas, G. Geochemical Perspective Letters, 105-114 (2017).
[2] G. Guo, Y. Chen, Y. Li, JOM 40 (7), 28–31 (1988).
[3] J.B. Hedrick. Mineral Commodity Summaries 2008: Scandium. US Geological Survey (2010).
[4] J.T.S. Irvine, T. Politova, N. Zakowsky, A. Kruth, S. Tao, R. Travis. Proceedings of the NATO Advanced Research Workshop on Fuel Cell Technologies, State and Perspectives, Kyiv, Ukraine, 35–47 (2004).
[5] Z. Ahmad. J.of Material, 55, 35–39 (2003).
[6] F.T. Ciacchi, S.P.S. Badwal, J. Drennan. J. Eur. Ceram. Soc. 7, 185–195 (1991).
[7] V.A. Shalomeev, N.A. Lysenko, E.I. Tsivirko, V.V. Lukinov, V.V. Klochikhin. J. Metal Science and Heat Treatment, 50 (1-2), 34-37 (2008).
[8] A. Maulana. M.Phil. Thesis, Australian National University, Canberra, Australia (2013).
[9] W. Hamilton. U.S. Geological Survey Professional Papers, 1078, 345 (1979).
[10] A. Kadarusman, S. Miyashita, S. Maruyama, C.D. Parkinson, A. Ishikawa. Tectonophysics, 392, 55-83 (2004).