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Mineralogical and geochemical characteristics of a serpentinite-derived laterite profile from East Sulawesi, Indonesia: Implications for the lateritization process and Ni supergene enrichment in the tropical rainforest

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ABSTRACT

To evaluate the lateritization process and supergene Ni enrichment in the tropical rainforest, a well developed laterite profile over the serpentinite in the Kolonodale area of East Sulawesi, Indonesia, has been investigated using field geology methods, mineralogical and geochemical techniques. Three litho-stratigraphic horizons over the bedrock are distinguished from bottom to top: the saprolite horizon, the limonite horizon, and the ferruginous cap. In general, the profile is characterized by (1) a depth-related pH ranging from 5.56 to 8.56, with a higher value in the saprolite horizon and a lower value in the ferruginous cap, (2) a highly variable organic matter concentration from 1.11% to 4.82%, showing a increasing trend from bottom to top, (3) a progressive mineral assemblage transition from the silicate mineral dominant (mainly serpentine) to the Fe-oxyhydroxide dominant (mainly goethite), and (4) a typical laterite geochemical pattern with an increase of Fe, Al, Mn, Cr and Ti but a decrease of Mg, Ca, Na and K upward from the bedrock. The highest concentration of Ni (up to 11.53%NiO) occurs in the saprolite horizon, showing nearly 40 times richer compared to the bedrock. The mineral evolution during the lateritization process shows various paths from the primary minerals to altered minerals, which is integrally affected by the nature of the primary minerals and environmental conditions. Garnierite, as a significant ore mineral formed by the secondary precipitation processes in the study profile, is identified as a mixture of talc- and serpentine-like phases. The mass-balance calculation reveals that there are diversified elemental behaviors during the serpentinite lateritization under the rainforest conditions. In particular, Ni, as the ore-forming element in the laterite profile, is associated closely with the pH environment, organic matter concentration and mineral evolution during the lateritization process.

The findings of the present study support a four-stage evolutional model for the lateritization process: the ferruginous saprolite development (stage I), the limonite development (stage II), the silicate saprolite and ferruginous cap development (stage III), and the precipitation of secondary minerals (stage IV). Due to this multistage process, there is a progressive Ni-enrichment in the laterite profile.

1. Introduction

Laterite soils derived from ultramafic rocks have been well documented, not only due to the scientific interest in understanding the supergene processes on the surface of the Earth (Wilson, 2004; Garnier et al., 2009), but also to the economical significance of the laterite-type nickel ore (Elias, 2002; Gleeson et al., 2004; Dalvi et al., 2004; Mudd, 2010; Butt and Cluzel, 2013). Nickel deposit of this type accounts for over 60% of the world's nickel resource and nearly 40% of the annual global nickel production (Berger et al., 2011). Globally, there are extensive outcrops of ultramafic rocks in tropical or subtropical environments at present and along the geological history, and these places tend to develop Ni-laterite soils, such as in New Caledonia, Western Australia, West Africa, Central America, Brazil and Balkans. Such Ni-laterite soils have received a great attention in economic geology, and a large

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number of related articles have been published in the last decade (e.g., Gleeson et al., 2004; Freyssinet et al., 2005; Fouateu et al., 2006; Lewis et al., 2006; Wells et al., 2009; Thorne et al., 2009, 2012; Golightly, 2010; Roqué-Rosell et al., 2010; Butt and Cluzel, 2013).

In Asia, Ni-laterite soils overlying the ultramafic rocks are well developed in the countries of Southeast Asia, especially Philippines and Indonesia (Brand et al., 1998; Elias, 2002), where numerous obducted ophiolite sheets are exposed to the intensive chemical weathering conditions of high rainfall and warm temperatures. Many large scale Ni-laterite deposits have been discovered, such as Sorowako, Pomalaa and Surigao in this area, which contributes to make Philippines and Indonesia the third and fourth biggest individual Ni-laterite ore reserves in the world, respectively (Dalvi et al., 2004). However, the geological characteristics of the Ni-laterite soils over the ultramafic rocks in Southeast Asia, particularly in Indonesia, have not been fully studied. Until now, Indonesia has focused the attention mainly on the Sorowako area, Sulawesi Island (Golightly, 1979, 1981; Sufriadin et al., 2011). In addition, the knowledge of lateritization process related to the formation of the Ni-laterite is still tenuous since their geological characteristics vary from one to the other (Golightly, 2010).

The present study deals with a newly discovered profile derived from serpentinite, which is located in Kolonodale area, Sulawesi Island, Indonesia. We present a preliminary evaluation of our new data about field geology, mineralogy and geochemistry, providing a detailed information about the Ni-laterite soil in Indonesia. Also, our work helps to get a deep insight into the lateritization process and Ni enrichment mechanism during the serpentinite weathering in the tropical rainforest, which is useful for the future exploration of Ni resources in this region.

2. Geological and geographical setting

The K-shaped Sulawesi Island is at the convergence zone of three tectonic plates: Eurasian, Pacific, and Indian–Australian. Due to strong tectonic activities, the geological structure of Sulawesi Island is very complicated. Four lithotectonic belts are identified in this island (Fig. 1): the West Sulawesi Volcano-Plutonic Arc Belt, the Central Sulawesi Metamorphic Belt, the East Sulawesi Ophiolite Belt, and the Continental Fragments of Banggai-Sula, Tukang Besi, and Buton (Mubroto et al., 1994). Our study site, the Kolonodale area in Central Sulawesi province, is located in the East Sulawesi Ophiolite Belt.

The East Sulawesi Ophiolite Belt represents a part of the Circum Pacific Phanerozoic multiple ophiolite belts, which were emplaced through convergent plate processes in Cretaceous to Miocene (Hall and Wilson, 2000). It extends 700 km from north to south and outcrops more than 15,000 km^2 (Kadarusmana et al., 2004). Ultramafic bodies are widely exposed within this belt, consisting of lherzolite, harzburgite, and peridotite, with some dunite, pyroxenite and gabbroic dikes.

In the study area, peridotite is the dominant rock type in the ultramafic complex, and it has been widely metamorphosed at a moderate-high grade to form serpentinite. There are two other lithological units occurring in the surroundings of the ultramafic complex: alluvial and sedimentary lacustrine rocks of Quaternary and Cretaceous sedimentary rocks (Kadarusmana et al., 2004). Faults, fractures and joints, striking mainly in NNW direction, are largely observed in the ultramafic complex due to the regional tectonic activities.

Geographically, the climatic condition in the study area is typical of humid tropical region, with a rainfall of about 2000 mm per year and an average temperature of about 26 °C. The high temperature and abundant rainfall support a lush vegetation over the entire region. The terrain of the study area is characterized by a low-moderate relief with gently sloping surfaces. Under this environment, the outcrop of ultramafic rocks is subject to chemically weathering and forms thick lateritic soils.

3. Field regolith geology

In the study area, serpentinite, as the main bedrock, outcrops along the edges of the highlands and it can also be observed in the bottom of some shallow exploration wells. The outcrops of serpentinite are characteristics of dark green to black, massive texture with smooth surfaces, and usually broken up into irregular fragments along the fractures and joints.

From the bedrock upward, the laterite soil is widely developed mainly along the gentle slopes, ridges, and platforms of the highland. It occurs with a variable thickness and may be continuous or not. The average thickness is about 10 m, and the thickest part may exceed 30 m. A typical well developed laterite profile can be divided into three lithostratigraphic horizons based on the variations in color, texture and mineralogy. They are termed as saprolite horizon, limonite horizon and ferruginous cap from bottom to top (Fig. 2). The details of each horizon are as follows.

3.1. The saprolite horizon

It overlies the bedrock with an irregular and gradual contact. This horizon is commonly well developed along the gentle slopes, but to a less extent in the highland. It is fairly heterogeneous with a variable thickness ranging from 1 to 5 m, and with mixed colors such as yellowish-brown, grayish-yellow and grayish-green. The saprolite horizon is loose, porous and friable, and contains different proportions of fine-grained groundmass (earthy saprolite) and coarse-grained fragments or blocks (rocky saprolite) (Fig. 3C). The primary structure of the bedrock can be partly observed in the lower part of the saprolite horizon where the rocky blocks are abundant, whereas it nearly disappears in the higher part of this horizon in which the earthy groundmass are dominant due to a stronger weathering.

The silicate minerals (verified as the serpentine and smectite in the following analyses) are the dominant component of the saprolite horizon, which is similar to many silicate-type Ni-laterite profiles (Brand et al., 1998). Thus, this saprolite horizon is simply termed as silicate saprolite in this study, as mentioned by Freyssinet et al. (2005). It should be noted that there is another type of saprolite horizon, which is found locally in the shallow laterite profiles and its earthy saprolite is dominated by the ferriginous minerals (verified as the goethite and hematite in the following analyses). For comparison, the latter is termed as ferruginous saprolite corresponding to the description in the Cawse profile, Australia (Brand et al., 1998).

Garnierite, as a striking weathering product, is found in the saprolite horizon of our study profile. It shows a jade-green color and a vein-like texture (Fig. 3D), and mainly occurs in the joints and fractures of the lower part of the saprolite horizon. Locally, the garnierite vein may extend into the underlying bedrocks along the fault zone.

3.2. The limonite horizon

This horizon is developed above the saprolite horizon with a visible contact in color. Its thickness ranges from 1 to 10 m, and it is preferentially developed in the flat relief. This horizon is brownish-red to brownish-yellow in color, soft, porous, and fine-grained. Main features of the original mineral components and the structures of the bedrock have been destroyed. The mineralogy