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Comparative Analysis of Vertical Metal Zonation in Ginigalpelessa and Indikolapelessa Serpentinite Complex

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Abstract

Serpentinite deposits in Ginigalpelessa and Indikolapelessa Sri Lanka, are known to exhibit a high supergene enrichment of Ni, Cr, and Co in the regolith due to the prolonged weathering of the underlying serpentinite bedrock. However, no detailed studies have been conducted to determine the vertical zonation of these critical metals in these deposits. The vertical metal distribution of a deposit is significant to delineate its vertical metal enrichment patterns and mobilization which may lead to the identification of efficient exploration and extraction methods. Therefore, this study assessed the vertical zonation of Ni, Cr, and Co in both Ginigalpelessa and Indikolapelessa serpentinite deposits. Twenty-four soil (n=12) and weathered rock (n=12) samples from 4 soil horizons (O, A, B, C) in soil profile were collected and analyzed for Ni, Co, Cr, and Cu by ICP-MS. Our findings revealed high metal concentrations in the soil or highly weathered rock samples over the partially weathered rock samples. The Ginigalpelessa deposit demonstrated4 a higher concentration of Ni, Co, Cr, and Cu compared to the Indikolapelessa deposit. It observed that the concentrations of Ni, Co, Cr and Cu in the topsoil were lower compared to deeper horizons (A, B, and C) in some locations. This may have occurred due to the bioavailability of some metals like Ni, which accumulates in the plants and reduce the concentration in the soil. Conversely, the low bioavailability of Cr compared to the other metals have resulted high Cr concentrations in the surface horizon. In addition, previous studies found that Cr is immobile, whereas Ni and Co are scarcely mobile under the moderate acidic conditions in the serpentine soil. During the weathering process, the slightly acidic rainwater leaches these Ni-like metals from the O and A horizons, resulting their enrichment in the B horizon. However, further studies are necessary to identify the suitable leaching or extraction method to recover these metals from serpentine soil. Therefore, this research contributes to a deeper understanding of vertical metal zonation in serpentinite deposits to facilitate more efficient and sustainable exploration of valuable metals like Ni in serpentinite deposits.

Keywords: Weathering processes; Nickel (Ni), Inductively Coupled Plasma Mass Spectrometry (ICP-MS); Metal distribution; Sri Lanka.

1. Introduction

Globally, serpentinite deposits have been identified on every continent near convergent boundaries, and around 1% of the earth's surface consists of serpentinite and its associated soil [1]. The serpentinite deposits are derived from ultramafic rocks such as peridotite and pyroxenite rocks containing olivine and pyroxene minerals [2]. These minerals are altered by hydrothermal fluids in the tectonic plate margins, resulting in the formation of serpentine group minerals, such as lizardite ($MgSi_2O_5(OH)_4$), antigorite ($(Mg, Fe^{2+})_3SiO_5(OH)_4$), and chrysolite ($MgSi_2O_5(OH)_4$) [3]. Therefore, serpentinite is classified as a clay mineral under silicates mineral group in the mineral classification system [3]. Generally, the serpentinite deposits consist of various metals, including Ni, Co, Cu, Cr, Mn, V, Zn, and Pb, whereas the essential plant nutrients such as N, K, and P are low [4]. This limited availability of essential plant nutrients results in low plant diversity [3]. In addition, the metals such as Ni, Cr, and Co in the serpentine soils and plants affects human health and the local ecosystem [5].

The comparative analysis of vertical metal zonation of a deposit is essential for understanding vertical metal enrichment in each horizon within the soil profile. The serpentine soil profile consists of several distinct horizons including organic layer (O horizon), topsoil (A horizon), subsoil (B horizon), parent material (C horizon) and bedrock (R horizon) [6]. The O horizon is rich in organic materials, whereas the A horizon primarily consists of sand, silt, and clay with a significant amount of organic matter. Subsequently, the B horizon accumulates leached materials from the A horizon through the infiltration of rainwater; the C horizon contains geological materials and cemented sediments with the minimum biological activity; and finally, the R horizon is bedrock at the bottom of the soil profile [7]. In the serpentinite deposit profile, each horizon contains varying concentrations of metals [6]. Vertical zonation often reflects information about changes in environmental conditions, geological processes such as weathering, and the history of formation of mineral deposits [6]. The weathering processes of ultramafic rocks and the development of the weathered regolith profile vary across different locations due to factors such as climate, the characteristics of the parent material, and other environmental elements including topography, biota, and time [4]. Those factors may influence the accumulation of varying metal concentrations in different soil horizons of the deposit over time [6].

In Sri Lanka, there are six serpentinite deposits found along the geological boundary between the Highland and Vijayan complexes, namely Ginigalpelessa, Indikolapelessa, Ussangoda, Katupotha Yodhaganawa, and Rupaha [8]. However, this study only focuses on Ginigalpelessa and Indikolapelessa serpentinite deposits. As a tropical country, the average annual rainfall and temperature of Sri Lanka are really high resulting in an intense rock weathering rate [1]. Therefore, the weathering rate of rocks in Sri Lanka is high causing significant metal enrichment within the soil profile [5]. Although previous studies have identified some metals such as Ni, Co, Cr, and Cu [1], [5], their vertical distributions within the soil profile are yet to be studied in detail. These metals are considered critical that are essential for modern technologies, but their supply is limited due to their scarcity, increased demand, and geopolitical constraints [9].

This research aims to study the vertical metal zonation in the serpentine deposits of Ginigalpelessa and Indikolapelessa to determine Ni, Co, Cr and Cu enrichments in each identified horizon and analyze the changes between those zones. This analysis helps to determine which horizons have a high concentration of critical metals and the economic feasibility of mining these metals by considering the cutoff grade for each critical metal, particularly Ni (cutoff grade1.5–3%) [10]. Because the demand for Ni has been increasing these days while depleting high-grade Ni deposits [11]. Therefore, Ni extraction is carried out in low-grade deposits (<1%). Additionally, this study will be used to assess suitable mining methods such as phytomining, in-situ acid leaching, and electrokinetic mining for extracting metals from serpentine soil [12], [13], [14].

2. Material and Methodology

2.1 Study Area

Ginigalpelessa and Indikolapelessa are two areas of serpentinite deposits located close to Embilipitiya town in Uva province, Sri Lanka. The area of the Ginigalpelessa serpentinite deposit extends approximately 1 km^2 along the litho-tectonic boundary, whereas the Indikolapelessa serpentinite outcrop covers an area of nearly 0.7 km^2 (Figure 1) [8]. The deposits are surrounded by various rocks, such as charnockites, calc-gneiss, migmatites, and cordierite gneiss, and these deposits contain lizerdite, chrysolite, and antigorite serpentine minerals [1]. Both Ginigalpelessa and Indikolapelessa located in dry zone of Sri Lanka with lower rainfall. The soil exhibits a moderately acidic condition with an average pH of 6.34 [5].

Previous studies on metal concentrations in upper soil horizons (depth nearly 0-15 cm) in Ginigalpelessa and Indikolapelessa reveals how metals such as Ni, Cr bound to different substances in the soil. Ni primarily presents in the residual fraction, followed by significant association with iron (Fe) and manganese (Mn) oxides, organic matter, exchangeable fractions and carbonate mineral. Similarly, Cr is mostly in the residual fraction, followed by organic matter, Fe, Mn oxides, exchangeable fraction and carbonates. It helps to understand the complex interaction between soil and metal, mobility of metals and environmental impacts. Further research into other soil profiles on serpentinite deposits will be essential to broaden our understanding and refine management strategies for these metal-rich environments [3].

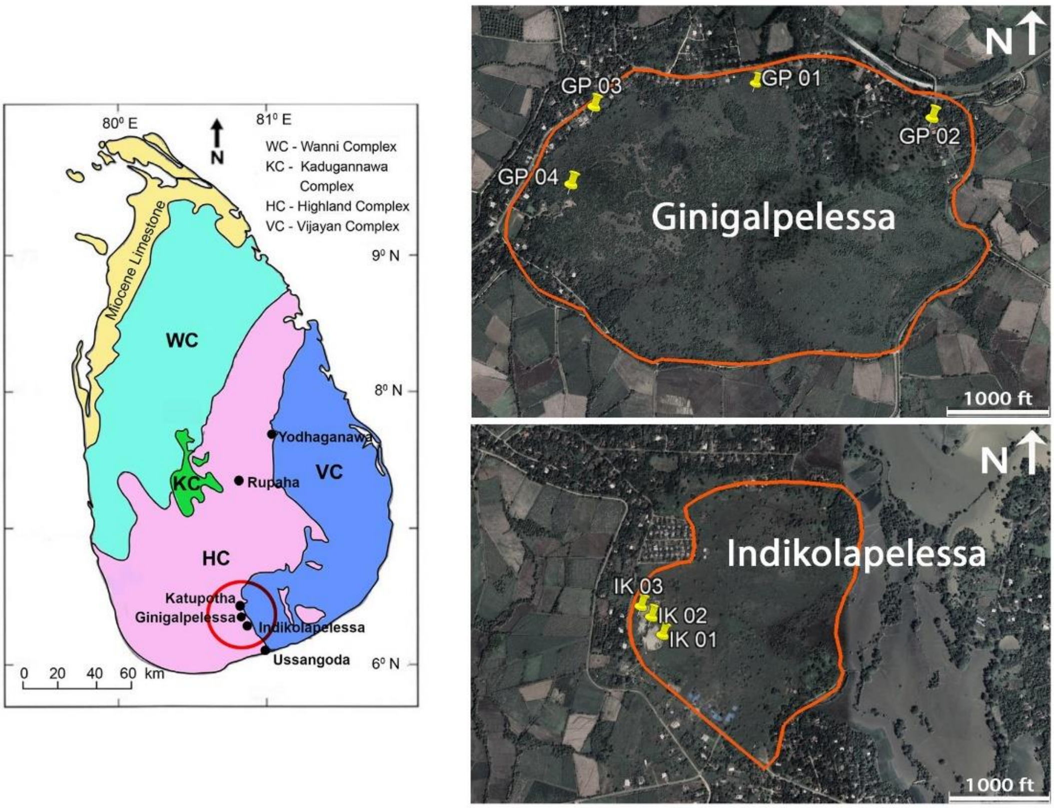

Figure 1: Ginigalpelessa and Indikolapelessa serpentinite bodies with sampling locations

2.2 Sample Collection

Samples were collected from four locations in Ginigalpelessa and three locations in Indikolapelessa. A total of twenty-four soil (n=12) and weathered rock (n=12) samples were taken from each identified horizon at every location. Two to five samples were collected vertically at each location from bottom to top of soil profile. As the bedrock depth is less than 2.5 meters in those areas, samples were obtained from available pits in Ginigalpelessa and Indikolapelessa.

2.3 Sample Analysis

All the samples were oven-dried at 105 °C for 48 hours to remove moisture from the samples. The rock samples were crushed using the laboratory jaw crusher, and then both soil and crushed rock samples were powdered in a laboratory Tema mill to reduce the particle size. Each produced powdered sample was sieved through a 63-micron sieve. The representative finely powdered samples were prepared using the coning and quartering methods for sample digestion. A 0.500 g of each prepared fine powdered sample was digested with a mixture of 3 ml HCl, 1 ml H_2O_2, and 1 ml HNO_3. All the chemicals used in solution preparation were in analytical grade. Each sample was heated uniformly at 120 °C for 3 hours. The samples were shaken to mix homogenously and then filtered through 0.45 µm filter paper. 1 ml of each sample was diluted up to 100 ml, and 10 ml of this diluted solution was taken for inductively coupled plasma mass spectrometry analysis (ICP-MS) (ICapQ-Thermo Fisher, Bremen, Germany) in the analytical laboratory at the University of Moratuwa [12]. Furthermore, three replicates and a standard series for each metal were analysed to maintain the precision and accuracy of the experiments.

3. Results & Discussion

In the Ginigalpelessa deposit, the O horizon contains highest average concentration of Ni compared to other metals while Co shows considerable concentration level. In A horizon, the average Ni and Co concentration increases up to 11, 312 ppm, 859 ppm respectively. Ni and Co is highly enriched in B horizon with the average concentration of 15,284 ppm and 1,219 ppm. Although Ni is the most enriched metal in C horizon compared to other metals, the average concentration of Ni decreases to 8,298 ppm. Co concentration also decreases in this horizon. Average concentration of Cr present in significant level in all horizons (O, A, B, and C), whereas the Cu concentration is relatively lower (Table 1) (Figure 2).

Ni has highest average concentration (4,804 ppm) in O horizon of the Indikolapelessa deposit and Cu shows relatively higher concentration compared to the same horizon in Ginigalpelassa. Average concentration of Ni increases to 5,976 ppm while Cr, Co, and Cu concentrations are slightly decreases from O horizon. All metal concentrations in B horizon decrease than the above horizon. The C horizon shows the lowest average metal concentrations among all horizons. The results indicate that the average concentration of Ni, Co, Cr, and Cu in Ginigalpelassa is greater than those metal concentrations in Indikolapelessa. Ni is the most enriched metal across all horizons, Co and Cr present in significant level whereas the Cu shows low concentration in both locations (Table 2) (Figure 3).

The ICP-MS result indicates that the concentration of Ni in each horizon in the Ginigalpelessa serpentinite deposit is higher than that in the Indikolapelessa deposit. Currently, the cutoff grade for Ni ranges from 1.5 to 3%, as the demand for Ni has been increasing while depleting high-grade Ni deposits [11].

Table 1 Average metal concentrations of each horizon in Ginigalpelassa

Horizons	Ni (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)
O Horizon	6626.95	195.10	651.75	22.70
A Horizon	11312.15	859.65	2097.65	17.00
B Horizon	15284.10	1219.33	3440.28	33.95
C Horizon	8298.40	182.62	584.70	10.62

Table 2 Average metal concentrations of each horizon in Indikolapelassa

Horizons	Ni (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)
O Horizon	4804.30	269.80	1057.55	35.95
A Horizon	5975.75	264.30	668.85	26.7
B Horizon	4610.67	183.67	758.93	12.27
C Horizon	4094.83	198.60	704.78	9.25

The maximum concentration recorded in the sample GP 04-B is 3% Ni, and the maximum average Ni content is 1.53% in the B horizon. However, the Indikolapelessa deposit has a maximum of 0.68% of Ni in IK 01-L2 (A), and the maximum average Ni content is 0.60% in the A horizon. In addition, the maximum concentrations of Co in Ginigalpelassa and Indikolapelessa are 0.32% in GP 04-B and 0.035% in IK 02-L4 (C), respectively. And the maximum average Co content in Ginigalpelessa and Indikolapelessa is 0.12% from the B horizon and 0.027% from the A horizon. Currently, the cutoff `grade for Co is 0.1% [12]. Hence, the Ginigalpelassa serpentinite deposit has higher Ni and Co concentrations in the B horizon than their cutoff grades (Figure 2). In addition, the concentrations of Ni, Co, Cu, and Cr show similar patterns in Ginigalpelessa location 02 because the samples were collected from disturbed organic-rich layers. Therefore, it is difficult to identify the exact concentration variation. Although Cr and Cu are present at quietly high concentrations in both deposits, the cutoff grades of these metals are higher than the concentrations in serpentinite deposits.

In most of the sampled locations, it was identified that the B horizon contains higher metal concentrations than other layers in the soil profile. Because the infiltration of rainwater mobilizes those metal ions from the organic-rich layer and A horizon, this process retains and accumulates metals within the B horizon [7]. In addition, the calculated average pH value is 6.34 in both serpentinite deposits. It indicates a moderately acidic nature (5.0<pH 5 [15]. Therefore, Cu does not show much notable change from organic rich soil to bedrock layer and has lower concentrations compared to Co and Ni. It was observed that Ni and Co concentrations in the organic layer are low compared to the middle layers in some sampled locations, as the low metal concentration may be due to the accumulation of Ni and Co in the plant biomass. Conversely, the high Cr concentration in the surface soil layers may happen due to the low bioavailability of Cr [12]. The low Ni and Co content in those areas may be due to the availability of hyperaccumulator plants which accumulates those metals from surface soil.

4. Conclusion

According to the result of ICP-MS, the maximum grade of Ni and Co from the B horizon of Ginigalpelessa is about 3% and 0.32%, respectively and have exceeded the cut-off grade. Therefore, there is a high potential that the Ginigalpelessa deposit will become a nickel and cobalt resource, even in low-grade. But the Indikolapelessa serpentinite deposit has a maximum of 0.6% Ni in the A horizon and 0.03% Co in the C horizon. These metals have a very low grade compared to the grade of the Ginigalpelessa deposit, as well as their cutoff grades. As Ni and Co are of low grade in the Ginigalpelessa deposit, conventional mining methods will not be suitable for extracting those metals accumulated within the B horizon. This method consumes more energy and generates large amounts of waste, making it economically unfeasible to recover those metals. Therefore, the study on comparative analysis of vertical metal zonation helps to select and implement one of the suitable sustainable mining methods (phytomining, acid leaching, and electrokinetic mining) to extract Ni and Co from local serpentine soils.

Table 3 Concentration of Ni, Co, Cr, and Cu in each horizon of Ginigalpelessa and Indikolpelessa

Location (Ginigalpelessa)	**Layer**	**Depth(m)**	**Ni(ppm)**	**Co(ppm)**	**Cr(ppm)**	**Cu(ppm)**
GP 01	O	0.44	7062.3	179.5	624.6	41.4
	B	0.74	3194.9	99.9	115.1	35.8
	C	0.82	2001.3	91.7	114.1	28.7
GP 02	O	0.1	6191.6	210.7	678.9	4.0
	A	0.325	8794.6	314.6	969.5	9.0
	B	0.635	9380.2	443.8	1099.4	11.8
	C	0.96	9889.7	232.9	775.3	8.3
	C	1.25	4952.0	224.5	965.8	0.4
GP 03	B	0.33	18414.1	1108.1	6004.7	31.5
	C	0.93	4405.3	165.8	284.2	4.0
GP 04	A	0.2	13829.7	1404.7	3225.8	25.0
	B	0.61	30147.2	3225.5	6541.9	56.7
	C	1.31	20243.7	198.2	784.5	11.7
(Indikolpelessa)						
IK 01	O	0.1	4171.1	238.6	1214.3	16.8
	A	0.3	6815.3	315.5	541.1	25.1
	B	0.8	3140.7	143.5	387.0	4.4
IK 02	B	0.25	5057.3	204.8	584.0	27.0
	C	0.7	3091.8	104.1	132.1	8.2
	C	1.3	3006.0	120.2	548.1	8.6
	C	2.1	6071.0	354.1	1353.6	16.4
IK 03	O	0.18	5437.5	301.0	900.8	55.1
	A	0.65	5136.2	213.1	796.6	28.3
	B	1.23	5634.0	202.7	1305.8	5.4
	C	1.9	4210.5	216.0	785.3	3.8

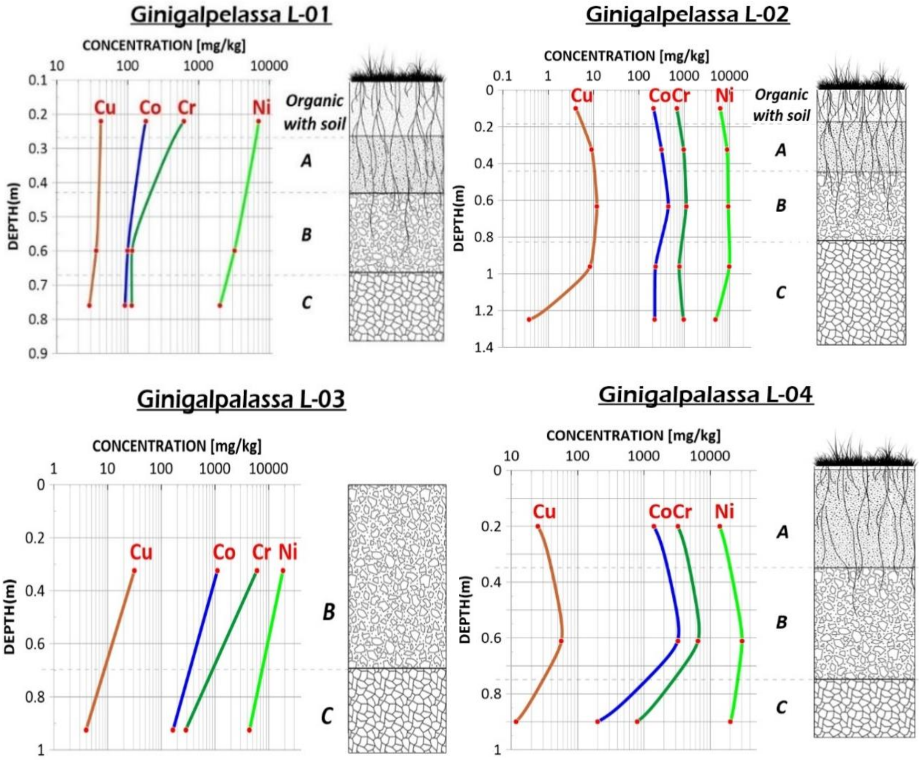

Figure 2: Distribution of Ni, Co, Cr, and Cu concentration with depth in Ginigalpelessa.

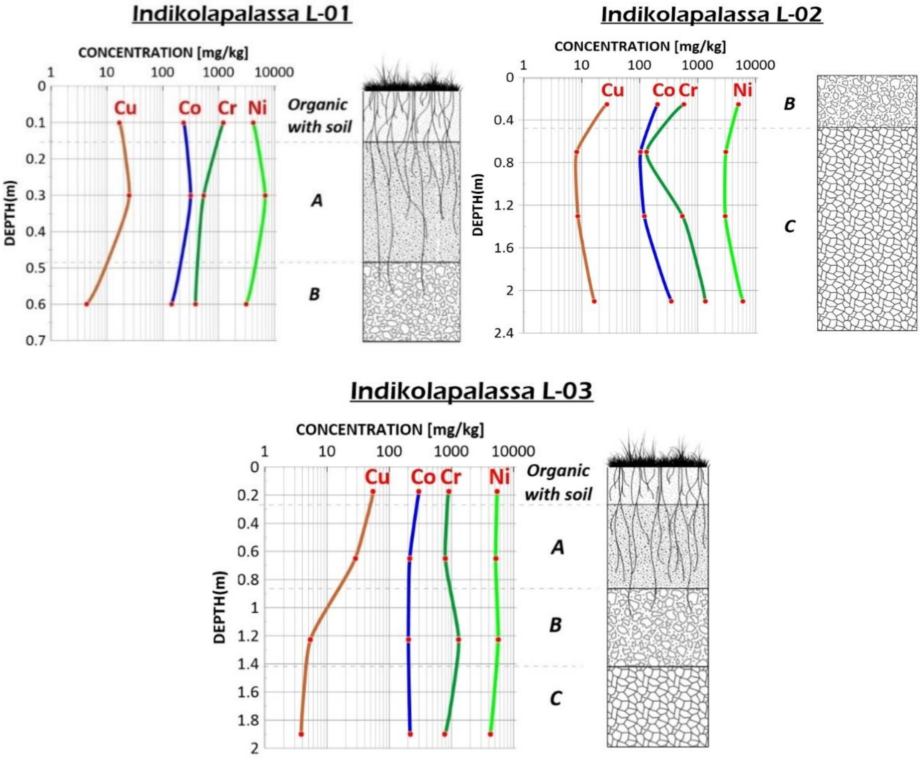

Figure 3: Distribution of Ni, Co, Cr, and Cu concentrations with depth in Indikolpelessa.

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