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GEOCHEMISTRY OF SERPENTINITE SOILS: A BRIEF OVERVIEW

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ABSTRACT

Even though serpentinite outcrops cover approximately 1% of total terrestrial land in the world, they have gained significant importance due to the high level of heavy metals such as Cr, Ni, Mn and Co leading to surface and groundwater contamination in addition to the dispersion via wind as particulate matter. Accordingly, both fauna and flora in the surrounding environment may be seriously affected via hyper accumulation. This paper is a brief overview of the geochemistry of serpentinite soils in a global context followed by findings from Sri Lanka. The geochemistry of serpentinite surroundings may differ from site to site as a result of different climatic conditions, in addition to the nature of the parent material. Serpentinite soil in Niquelandia, Brazil reported high amounts of Ni (73786 mg / kg) while approximately 60000 mg / kg of Cr has been reported in the New Caledonia serpentinite soils. In addition, reported Mn and Co concentration of Haut Limousin, France and Niquelandia, Brazil were 5886 and 980 mg / kg, respectively. Further, the distribution of heavy metals and other major elements along the weathering profile of serpentinite soil differs globally. Therefore, it is a timely need to investigate the relationship of pedology on heavy metal and major element distribution along the serpentinite soil profiles.

Keyords: Serpentinite, Geochemical background, Weathering, Chromium, Trace metal

INTRODUCTION

Serpentinite surroundings are noted for their elevated levels of Ni, Cr and Co (Alves et al., 2011; Becquer et al., 2003; Oze et al., 2004a). Although they occupy approximately 1% of the Earth's total exposed surface, potential bioavailability through agricultural activities and leaching to groundwater are anticipated from these serpentinite soil surroundings (Kelepertzis et al., 2013). Chemical and mineralogical evolution of the potentially toxic elements between the trace metal bearing bedrocks such as ultramafic serpentinites and the overlying soil horizon along weathering profiles are commonly found in many areas around the globe. Recently, Antibachi et al. (2012) reported Ni and Cr concentrations up to 2639 mg / kg and 856 mg / kg respectively in agricultural soils of the Mouriki–Thiva area, in central Greece, attributed to the occurrence and weathering of ultramafic rocks. Such high concentrations may potentially impact the food chain since the agricultural activities are common in many ultramafic surrounding regions causing a major concern. Hence, soil geochemical studies reflecting the geogenic concentrations of chemical elements (natural background) are of fundamental significance to estimate the extent of soil contamination, delineate potentially contaminated spots and to support better decision-making for environmental and human health protection. This study therefore aims to review the geochemistry of the serpentinite soil systems in the world including Sri Lanka.

GEOLOGICAL BACKGROUND OF SERPENT-INITE OCCURRENCES

The term ultramafic is generally used to describe igneous or metamorphic rocks, containing less than 45% silica (SiO_2) in addition to the high concentrations of metals such as Ni, Mg, Fe, Cr, and Co (Susaya et al., 2010). Serpentinite is a metamorphic rock formed due to low temperature (300-600 °C) hydrothermal alteration of ultramafic rocks and consist of one or more serpentine group of minerals such as lizardite ($Mg_3Si_2O_5(OH)_4$), chrysotile ($Mg_3Si_2O_5(OH)_4$) and antigorite ($(Mg,Fe^{2+})_3Si_2O_5(OH)_4$). As a result of serpentinization, a hydration and metamorphic transformation of ultramafic rocks such as peridotite and pyroxenite, which consist of Fe- and Mg-rich silicate minerals olivine ($(Mg,Fe^{2+})_2[Si_2O_4]$) and pyroxene ($XY(Si,Al)_2O_6$), from the Earth'mantle, above mineral groups are formed (Oze et al., 2008). Magnetite ($Fe^{2+}Fe_2^{3+}O_4$), Cr-rich magnetite ($Fe^{2+}(Fe^{3+},Cr)_2O_4$) and chromite ($FeCr_2O_4$) are the commonly associated minerals with serpentinites. In addition, mixed-composition spinels such as talc ($Mg_3Si_4O_{10}(OH)_2$), chlorite ($(Mg,Fe)_5Al[(OH)_8AlSi_3O_{10}]$), tremolite ($[Ca_2][Mg_5][(OH)_2Si_8O_{22}]$) and brucite ($Mg(OH)_2$) associate with serpenttinites (Oze et al., 2004b). Serpentinite soils are derived from the weathering of peridotite or serpentinite (Alexander 2004). Both peridotite and serpentinite have the same chemical composition except that serpentinite has about 13% more water and weathered surfaces are somewhat different from each other. Weathered peridotite surfaces are basically yellowish brown or reddish brown, while weathered serpentinite surfaces are light to white in colour (Alexander, 2004). Figure 1 shows the position of serpentinite in mineral classification system.

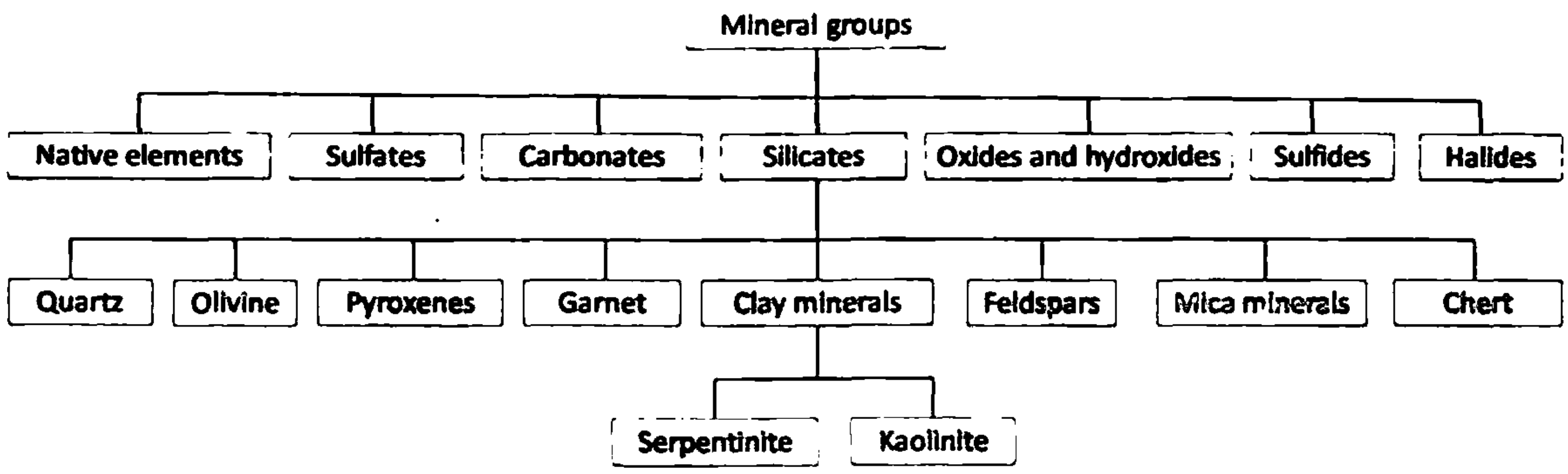

Fig. 1 Position of serpentinite in the mineral classification system.

DISTRIBUTION OF SERPENTINITE SOILS IN THE WORLD

Serpentinites and serpentinite soils cover approximately 1% of the total earth's surface while ophiolite is more commonly associated with these rocks and soil (Lee et al., 2001). In other words, serpentinite outcrops have been recognized in every continent except Antarctica. Although, serpentinites cover only a small area of the terrestrial landscape, wide distribution has been reported even in populated areas within the Circum-Pacific margin and the Mediterranean (Oze et al., 2004b). The majority of major ophiolitic serpentinite deposits are located close to the convergent margins. Further, serpentinite outcrops located in North America, Europe and Australian continents are well documented (Cheng et al., 2011). The extent of serpentinite outcrops in California, Oregon and Washington along the western coast of North America is approximately 2860, 1170 and 520 km^2, respectively (Morrison et al., 2009). Irregularly distributed serpentinite outcrops are located in the Tras-os-Montes region in the northeast region in Portugal (Alves et al., 2011) and Alps and Apennienes of north-western Italy (Bonifacio et al., 1997). It is reported that weathering of serpentinites occurs in the South-East part of the Pan-African belt in Cameroon (Ndjigui et al., 2008). In addition, Albania has a large terrestrial area with serpentinites containing the world's third largest nickel mineral deposit (Shallari et al., 1998). Figure 2 shows the selected serpentinite outcrops in the world.

CHARACTERISTICS OF SERPENTINITE SOILS

Pedological studies of serpentinite and serpentinite soil has been widely investigated. Weathering of serpentinite and serpentine rocks differ from site to site as a result of different climatic conditions in addition to the nature of parent material and other factors such as topography, biota and time (Oze et al., 2004b). Therefore the chemistry of these soils may vary significantly from location to location.

MINERALOGY OF SERPENTINITE SOILS

As discussed, the mineralogy of serpentinite soil catena is strongly influenced by the geochemistry and mineralogy of parent material as well as the climatic conditions of weathering. Despite the occurrence of the primary or secondary minerals, serpentinite and spinels inherited from the ultramafic bedrock still remain predominant. Therefore, the bioavailability, mobility and potential toxicity of the heavy metals largely depend on the mineral speciation corresponding to their chemical binding forms (Kelepertzis et al,. 2013). Based

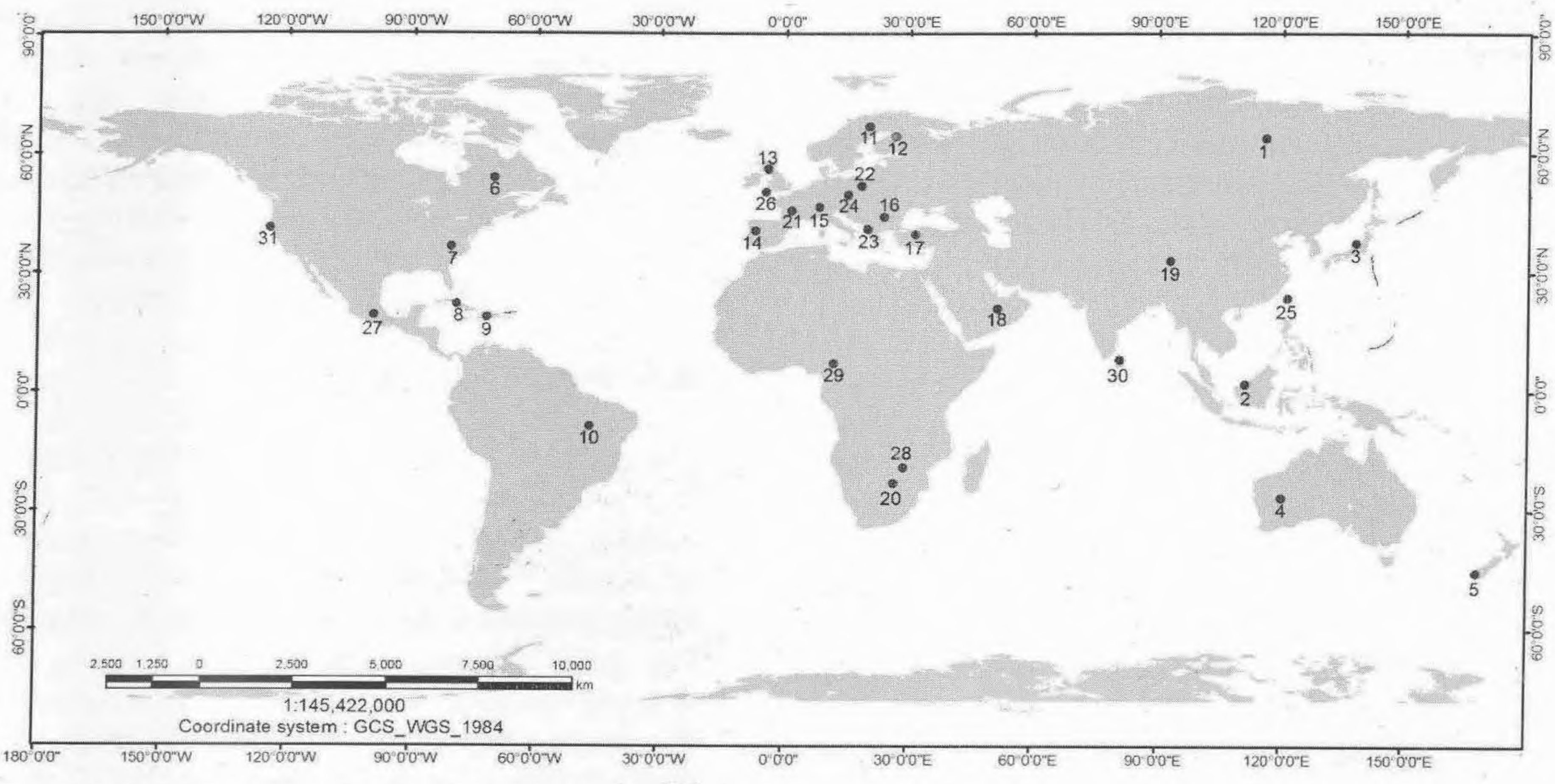

Fig. 2 Selected serpentinite soil localities in the world.

Note: 1. Siberia, 2. Philippines, 3. Japan, 4. Western Australia, 5. New Zealand, 6. Newfoundland, USA, 7. Maryland, USA, 8. Cuba, 9. Puerto Rico, 10. Brazil, 11. Norway, 12. Finland, 13. Scotland, 14. Spain, 15. Italy, 16. Greece, 17. Turkey, 18. Oman, 19. Burma, 20. South Africa, 21. France, 22. Poland, 23. Albania, 24. Czech Republic, 25. Taiwan, 26. England, 27. Mexico, 28. Zimbabwe, 29. Cameroon, 30. Sri Lanka, 31. Nickel mountain, USA

on X-ray diffraction results, the serpentinite mineral group consists of several associated minerals. A generic formula that includes all members in the serpentine group is $(Mg,Mn,Fe,Co,Ni)_{3-x}SiO_2O_5(OH)_4$. Antigorite $((Mg,Fe^{2+})_3Si_2O_5(OH)_4)$, lizardite $(Mg_3Si_2O_5(OH)_4)$ and chrysotile $(Mg_3Si_2O_5(OH)_4)$ are the most common minerals in serpentine group (Bayliss, 1981). Morphologically, antigorite has a platy and fibrous structure while lizardite has a platy structure. In the case of chrysotile, it displays hollow tube morphology. Chrysotile is composed of polymorphous minerals as a result of different crystal lattice. These different types are clinochrysotile, orthochrysotile and parachrysotile (Page, 1968).

Mg-rich and Fe-rich clay minerals such as Ni- and Cr-bearing smectites, vermiculites and/or chromite–silicate mixtures are produced due to weathering of ultramafic rocks under temperate climate (Kierczak et al., 2007). Further, though secondary minerals such as amorphous Fe oxides and goethite consist of higher concentrations of Ni and Cr, serpentinite and spinels provide a host for Ni and Cr predominately (Chardot et al., 2007). One recent study reported the mineralogical characteristics of serpentinite soils in Thiva Valley, Greece in detail (Antibachi et al., 2012). Further they have found that the Cr is dominantly bound in the crystal structure of chromite while Ni is hosted in olivine and serpentinite. However, not many studies have reported such aspects of serpentinite soil. Recently, Kelepertzis et al. (2013) investigated that Ni is basically bound in serpentine (0.5 wt % of NiO) in addition to the occurrence in secondary weathering products such as smectites and goethite, 0.5 and 1.1 wt % of NiO, respectively. Moreover, Cr primarily occurred in chromite (54.7 wt % of Cr_2O_3) and Cr-magnetite and Cr silicates such as enstatite to a lesser extent (12.2 wt % and 0.8 wt % of Cr_2O_3, respectively).

GEOCHEMISTRY OF SERPENTINITE SOILS

The chemical characteristics such as mineralogical and compositional variation of serpentinite outcrops are broadly investigated globally. Prominent chemical properties of serpentinites are listed below.

(1) High concentrations of potentially biologically toxic elements such as Cr, Ni, Mn, Co, Cd and Fe.

Serpentinites act as a possible source of non-anthropogenic metal contamination site by releasing of heavy metals into the surrounding environment during the natural weathering process. It is reported that in the tropical environment, serpentinite soils are extremely rich in Ni and Cr and results in favorable conditions for growth of microbes.

These metals can be easily leached into the environment though lower in temperate regions (Amir and Pineau, 2003). The toxicity of serpentinite soils is generally termed as the 'serpentine syndrome' leading to poor primary productivity and endemism (Oze et al., 2008).

(2) Low Ca / Mg ratios results in strong chemical fertility limitations for plants.

The abundance of Mg released from serpentinite weathering makes it the dominant cation on soil exchange sites, resulting in the characteristically low exchangeable Ca/Mg ratios. Under temperate climate, Mg is partially leached during soil formation due to incomplete hydrolysis while under tropical climatic conditions, complete hydrolysis occurs resulting in leaching of almost all available Mg (Kierczak et al., 2007).

(3) Low concentrations of important plant nutrients including N, P and K.

In serpentinite soil, exchangeable Mg concentrations are high and exchangeable Ca concentrations are low resulting in deficiencies in plant nutrients such as N, P and K. With the presence of low amounts of essential plant nutrients, plants have been adapted morphologically and physiologically to this harsh environment resulting in high endemism and poor diversity of plants (Weerasinghe and Iqbal, 2011). It is reported that unusual plants such as carnivorous cobralily (Darlingtonia californica) grow on this unfavorable and hostile environment (Oze et al., 2008).

SOIL SOLUTIONS AND WATER

Unlike organic substances, it is impossible to degrade the trace metals in soil and water leading to risks in the biosphere. The availability of metals in the soil and their toxicity affect living organisms and this is mainly governed by the metal release from the soil matrix. This process is controlled by climatic conditions such as temperature and water availability, soil characteristics such as texture, pH, redox potential, cation exchange capacity, carbonate, organic matter and oxides content (Alves et al., 2011). In addition, interactions between soil, plants and microorganisms within the rhizosphere can affect metal availability through chemical and biological processes (Menzies et al., 2007). In early weathering stage of serpentinites, magnesium and silicon leach into the soil profile (Caillaud et al., 2009). Serpentinites consist of high amounts of toxic

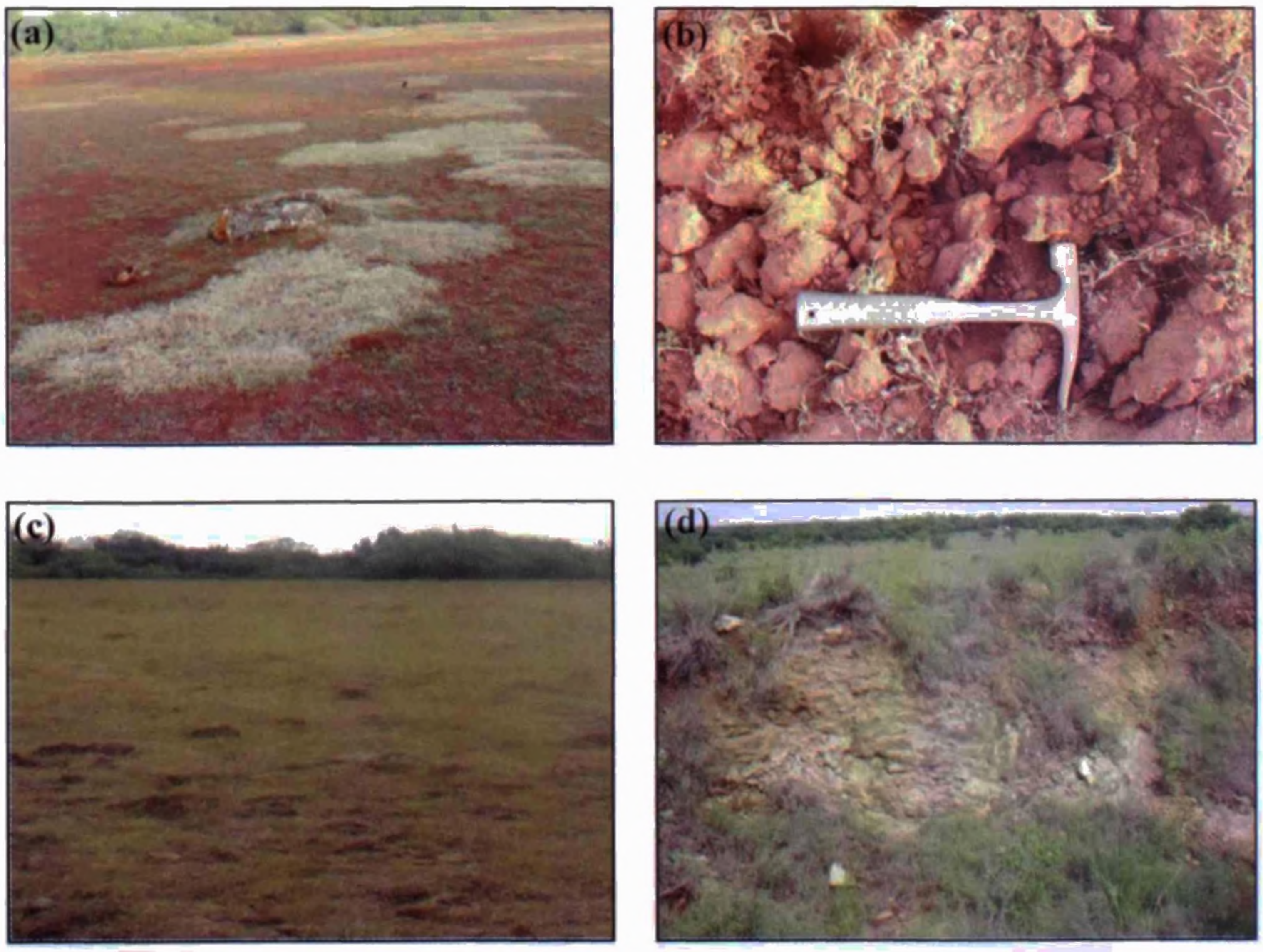

Fig. 3 Surrounding environment at Ussangoda, Yudhaganawa and Indikolapelessa serpentinite outcrops (a, c and d respectively) and serpentine soil at Ussangoda (b).

elements such as Cr and Ni which may be released during weathering into soil, surface water and ground water.

SOIL ORGANIC MATTER

Soil organic matter (SOM) acts as a reservoir for many plant nutrients in addition to the substantial part of the cation exchange capacity of soils (Powlson et al., 2012). Even a small amount of SOM is able to influence soil properties to a marked extent. In case of serpentinites, SOM greatly influences the geochemistry and pH buffering capacity. SOM concentration of serpentinite in temperate regains is quite high compared to that in tropical regions (Oze et al., 2004b). Due to relatively low clay and organic matter content and the rocky nature of the serpentinite soil, low water holding capacity results in the high permeability (Weerasinghe and Iqbal, 2011). Further, it is reported that toxic metals such Cr, Ni and Co release from serpentinite outcrops due to the oxalic and citric acids which are produced by SOM (Schreier et al., 1987). In addition, fulvic and humic acids which are known to complex cations such as Cr(III), Fe(III) and Mn(II) are in position to make stable organometallic complexes (Kaupenjohann and Wilcke, 1995).

CHROMIUM GEOCHEMISTRY OF SERPENTINITE SOILS

SOURCES OF CHROMIUM IN SERPENTINITE AND SERPENTINITE SOIL

Chromium-spinel, often referred to as chromite [$FeCr(III)_2O_4$], acts as the primary source of Cr in serpentinites (Oze et al., 2007). In serpentinite and serpentinite soil, chromium is retained in the form of Cr(III). It is reported that serpentinite pyroxenes such as augite (<1 Cr wt%) and enstatite (<10 Cr%) contain Cr in significant concentrations (Oze et al., 2004b). Partial oxidation of Fe(II) presents in olivine and pyroxene forms magnetite during the serpentinization process. Cr(III) derived from primary containing phases of chromite and pyroxene may isomorphically substitute into the Fe(III) site of magnetite as a result of similar size (octahedral radii: Cr(III)=0.615 Å and Fe(III)=0.643 Å) and charge properties. It has been investigated that chromium concentrations in magnetite are as high as 13 wt% (Oze et al., 2004a). In addition, serpentine minerals such as antigorite, lizardite and chrysotile, consist of low concentrations of Cr. Moreover, Chromate minerals such as crocoites ($PbCrO_4$) which is restricted to limited areas in the world such as Australia, Tasmania and the Urals, are extremely rare in serpentinites (Crane et al., 2001).

On the other hand, hydrothermal and CO_2 metasomatism of ultramafic rocks along the convergent plate margins generally produce Cr-silicate minerals [(Cr-muscovite: <19 Cr wt %), (Cr-garnet: <20 Cr wt %), (Cr-epidote: <13 Cr wt %) and (Cr-clorite: <10 Cr wt%)] (Oze et al., 2004b). Taking into account, any of these minerals are in a position to act as possible sources for Cr in soils produced due to weathering of serpentinites and their hydrothermal and CO_2 metasomatic derivates.
Chromium bearing sites in serpentinite soil have been investigated. Soil minerals such as Fe(III) oxides and Fe(II)(oxy) hydroxides provide the host structural and surface sites to sequester Cr(III). Fe(III)–containing oxides such as magnetite and hematite which are capable of readily sorbing Cr(III) via inner-sphere surface complexes and forming low-solubility precipitates. As a result of similar size and charge properties, clays such as smectites and vermiculites provide structural and surface sites for octahedral substitution of Cr(III) for Al(III). It is reported that Cr concentrations in the clay-sized fraction can achieve concentrations of approximately 1000 mg / kg in serpentinite soils. Further, Cr in serpentinite soils is mainly residually bound in silicate structures, indicating clay minerals according to the extraction experiments (Oze et al., 2004b).

DISTRIBUTION OF CHROMIUM IN SERPENTINITE SOIL

Typical chromium concentration in soils and rocks ranges between 0 to 200 mg / kg (Becquer et al., 2003). The average Cr concentration of global soils recorded as 126 mg / kg (Sposito, 2008). Although chromium concentrations vary significantly due to the chemical and mineralogy of parent material and soil forming factors such as climate, topography, time and organic matter in serpentinite occurrences globally, chromium concentrations above 10,000 mg / kg have been reported. Chromium concentration of approximately 60,000 mg / kg has been reported in the New Caledonia soils. Further, some serpentinite soils have shown Cr concentrations as low as 29 and 66 mg / kg (Oze et al., 2004b). Variation of Cr concentrations with respect to the soil depth has been investigated by performing chemical extractions on serpentinite soils which provide additional information with respect to Cr availability and the minerals and complexes in which Cr may reside in the soil. In addition, Oze et al. (2004) investigated that residual Cr-bearing minerals such as chromite and Cr-magnetite are highly resistant to weathering in the protolith in Jasper Ridge serpentinite soils.

NICKEL AND OTHER TRACE METALS IN SERPENTINITE SOILS

Although typical Ni concentration of soils ranges between 5 to 500 mg / kg, in serpentinite soils it may exceed 10,000 mg / kg (Proctor, 1999). It is observed that plants growing on non-serpentinite soils and serpentinite soils show significant differences in their Ni content, ranging from 0.1 to 5 mg / kg and up to 100 mg / kg, respectively. In addition, some endemic plant species growing on serpentinite soils contain over 1000 mg / kg of Ni (Alves et al., 2011). Alves et al. (2011) observed that approximately 14% of the total Ni is bound with hydrous Mn oxides, 1% with amorphous Fe oxides and 12% with well-crystallized Fe oxides. It reveals that the majority of Ni sinks into specific phyllosilicates leading to their inaccessibility in the chemical extractions used. Ferralitic soils whose chemical composition is mainly governed by iron and manganese oxides are produced under tropical conditions. The main Ni bearing phase of ferralitic soils is goethite. Kierczak et al. (2007) reported that Ni mobility is minimized by formation of smectite derived from the weathering of serpentinite. Mesh textures as a Ni-host phase in serpentinite soil has a high Ni concentration than veins (3720 mg / kg and 2000 mg / kg, respectively) (Caillaud et al., 2009). In addition, EMPA results show that Ni concentration is quite high in weathering products such as vermiculite and smectite than chlorite (5367, 4781 and 1450 mg / kg, respectively).

In addition to the Cr and Ni, Mn, Co, Cu, Pb and Zn are found in markedly high concentrations in serpentinite soil profiles. Human exposure of Mn may occur due to the ingestion and inhalation of serpentinite dust particles resulting in common symptoms such as ataxia, dementia, anxiety and manganism. In the case of plants, producing dark specks on leaves and dying at leaf margins are possible symptoms as a result of excess Mn uptake. For Mn, hydrous Mn oxide is the predominant form in the serpentinite soils (69±10% of total Mn) (Alves et al., 2011).

Cobalt is considered as one of the essential elements for maintaining good health in humans and animals. Plants are able to accumulate small amounts of Co and excess uptake leads to dysfunction of plants. Under more acidic conditions, Co in serpentinite and serpentinite soil may be released into the surrounding environment (Caillaud et al., 2009).

GEOCHEMICAL VARIATION IN WEATHERING PROFILES OF SERPENTINITE SOIL

Serpentinite weathering may produce a high geochemical background with trace metals anomalies in the soil profile (Caillaud et al., 2009; Kierczak et al., 2007). In general, geochemical background studies for serpentinite mainly focuses towards comparison of trace metal concentrations in various weathered horizons along the soil profile with the trace metals content of the parent rock (Shallari et al., 1998). The distribution of trace metals can be determined either at the profile scale or at the mineral scale (Caillaud et al., 2009). Nevertheless, studies relevant to mineral speciation and mobility of trace metals in serpentinite soil profile are rarely reported under temperate and tropical conditions.

Geochemical variation of bulk samples at profile scale confirmed that trace metal concentration is found in markedly high concentrations compared to those of the Earth's crust (Table 1). The weathering processes obviously concentrate the trace metals in the secondary phases and increase the geological anomaly towards the soil surface. Nevertheless, their distribution does not show the same trend at all investigated weathering profiles (Table 1). This exhibits the variation of weathering rate of trace metal-bearing minerals and the trace metal mobility in soil profile (Quantin et al., 2008).

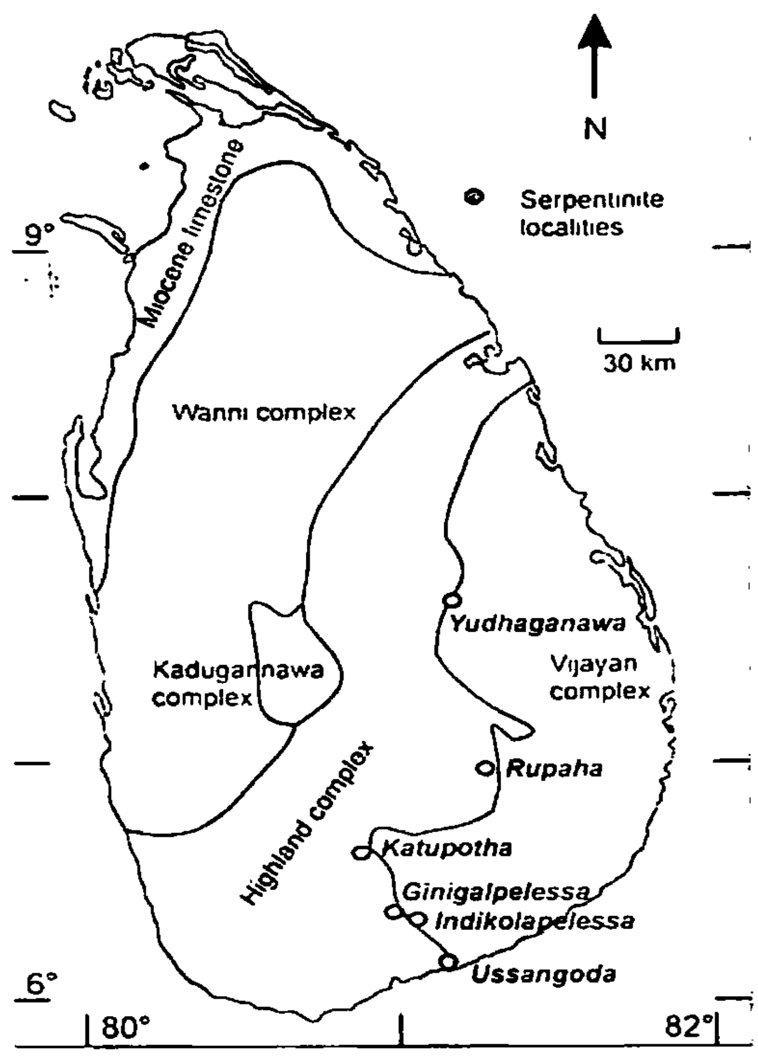

Fig. 4 Serpentinite localities in Sri Lanka along the lithological boundary between Highland and Vijayan Complexes.

The distribution of trace metals along the profile will thus depend on the weathering susceptibility of their initial host minerals. Climatic conditions determine the mineral speciation in serpentinite soil. Moreover, local temperate climatic conditions such as humidity, rain, snowfall duration and temperature variations can be affected to soil forming process (Kierczak et al., 2007). Caillaud et al. (2009) reported that serpentinite rock consists of 70-75% serpentine minerals, 10-15% chlorite and 5-8% magnetite and chromite minerals in Haut Limousin, France. Main minerals in parent rock, Szklary Massif, Poland represents 40-50% serpentine, 35-40% forsterite, 10-15% amphiboles, 8-10% spinel and 5% chlorite (Kierczak et al., 2007). Whereas, bed rock of Nove Dvory, Czech Republic is composed mainly by serpentine and olivine, orthopyroxenes and clinopyroxenes are the minor components (Quantin et al., 2008). Moreover, Kierczak et al. (2007) reported that some non stable primary minerals such as olivine, serpentine and chlorite are present in the A horizon. This observation may be due to the slow weathering rates under temperate climate and former hydrothermal processes affecting the parent rock fabric (Kierczak et al., 2007).

Table 2 shows the relative variations of major elements along a soil profile and that may represent the rock-forming mineral behavior during weathering. High levels of magnesium (wt% as MgO), low calcium and aluminium (wt% of CaO and Al_2O_3) and extremely low levels of sodium and potassium (wt% of Na_2O and K_2O) are contained in serpentinite rock and its weathering products along the soil profile. Mg ratio between weathered horizons and the parent rock sample is quite low in all investigated locations. The reason may be Mg has under gone partial leaching due to incomplete or complete hydrolysis under temperate or tropical climate conditions (Caillaud et al., 2009).

SERPENTINITE GEOCHEMISTRY OF SRI LANKA

Geological studies have identified six serpentinite outcrops so far in Sri Lanka. These serpentinite outcrops have a deep-seated origin by observing their northward orientation close to the litho-tectonic boundary (Hewawasam et al., 2014). Figure 3 shows the locations of some serpentinite outcrops in Sri Lanka. The prominent feature of all identified serpentinite outcrops is that all are located on the lithotectonic boundary of Highland and Vijayan complexes. The six locations are Ussangoda, Indikolapellessa, Ginigalpellessa, Katupota, Rupaha and Yudhaganawa (Figure 4). Among six serpentinite outcrops, Rupaha deposit is situated towards the center of the country while other five deposits are located in alignment with the contact between the Highland and Vijayan complexes (Fernando et al., 2013).

Ussangoda serpentinite outcrop is located in the southern coastal end. The extent of this deposit is recorded as 3 km^2 and soils mainly consist of hematite with fine-grained clayey sand leading to lateritic reddish hue (Rajakaruna and Bohm, 2002). Plant diversity with respect to the soil

characteristics for the Ussangoda serpentinite deposit was investigated and a remarkable difference in plant diversity between serpentinite and non- serpentinite soil.which has high plant families and species was observed (Weerasinghe and Iqbal, 2011). Additionally, high concentration of Ni (560-830 ppm) had been recorded in five plant species growing on Ussangoda serpentinite soil. Moreover, Ni and Mn release kinetics from Ussangoda serpentinite

Table 1 Trace metal concentration with respect to the depth in different serpentinite locations in the world

Location	Depth (cm)	Concentration (mg / kg)								Reference
		Mn	Co	Ni	Cr	Cd	Cu	Pb	Zn	
Earth's crust		716	24	56	126	0.1	25	14.8	65	Sposito (2008)
Prrenjas, Albania	15	-	476	3579	3865	14	36	172	93	Shallari et al. (1998)
Bitincka, Albania	15	-	184	1737	513	4	6	80	52	Shallari et al. (1998)
Gjegjan, Albania	15	-	289	1104	574	4	27	87	49	Shallari et al. (1998)
Pogradec, Albania	15	-	259	2442	635	5	8	98	63	Shallari et al. (1998)
Klamath mountains, USA	0-12	1750	173	2718	1247	-	24	-	72	Alexander (2014)
Samar island, Philippines	0- 20	-	-	1840	-	-	-	-	-	Susaya et al. (2010)
California, USA	10- 20	-	-	4060	11670	-	-	-	-	Morrison et al. (2009)
Morais Massif, Portugal	0- 15	2400	-	2800	2800	-	29	-	73	Alves et al. (2011)
Nove Dvory, Czech Republic	Few meters	-	103.2	3054	2682	-	-	-	-	Quantin et al. (2008)
Haut Limousin, France	60- 80	5886	724	4142	7466	-	-	-	-	Caillaud et al. (2009)
Haut Limousin, France	80- 100	4569	750	5320	6756	-	-	-	-	Caillaud et al. (2009)
Haut Limousin, France	100-120	1936	248	4625	8675	-	-	-	-	Caillaud et al. (2009)
Haut Limousin, France	120-140	465	117	4018	5812	-	-	-	-	Caillaud et al. (2009)
Haut Limousin, France	Rock (>140)	620	86	1587	2262	-	-	-	-	Caillaud et al. (2009)
Niquelandia, Brazil	0- 15	-	980	3606	5185	-	-	-	-	Garnier et al. (2009)
Niquelandia, Brazil	15-30	-	115	25767	8066	-	-	-	-	Garnier et al. (2009)
Niquelandia, Brazil	30-70	-	295	73786	5960	-	-	-	-	Garnier et al. (2009)
Niquelandia, Brazil	70+	-	189	32216	9400	-	-	-	-	Garnier et al. (2009)
Shih-Tao, Taiwan	0- 15	-	-	3222	3192	-	-	-	-	Cheng et al. (2011)
Shih-Tao, Taiwan	15-50	-	-	2352	2548	-	-	-	-	Cheng et al. (2011)
Shih-Tao, Taiwan.	50-80	-	-	3458	3146	-	-	-	-	Cheng et al. (2011)
Shih-Tao, Taiwan	80-110	-	-	3991	3214	-	-	-	-	Cheng et al. (2011)

soil have been studied by Rajapaksha et al. (2012). The study revealed that Ni and Mn are dominantly released from antigorite which is the prominent mineral in that soil. Moreover, with

the presence of birnessite, Cr(VI) formation from Cr(III)-bearing silicates is increased and Cr(VI) production rate was decreased by 80% due to the humic matter suggesting that absence of Cr(VI) in solid solution in Ussangoda serpentinite soil is occurred as a result of high amount of humic matter content (Rajapaksha et al., 2013).

Dissanayake and Riel (1978) investigated the Indikolapelessa serpentinite petrology and geochemistry in detail. Indikolapellessa and

Ginigalpellessa serpentinite deposits have been described as more than 90% of pyroxene and olivine rich and rest consisted of orthoclase, plagioclase, diopside and

magnetite (Dissanayake, 1982). The area of Indikolapellessa and Ginigalpellessa outcrops are estimated to be approximately 7 and 1 km^2, respectively. According to the textures and

Table 2 Major element compositions of investigated serpentinite rocks and soil in the world

Location	Depth (cm)	Major elements (wt%)									Reference
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	
Haut Limousin, France	60- 80	32.69	7.32	25.59	16.01	0.26	0.07	0.19	0.16	-	Caillaud et al. (2009)
Haut Limousin, France	80- 100	33.80	6.26	24.36	14.92	-	-	0.06	0.09	-	Caillaud et al. (2009)
Haut Limousin, France	100-120	39.29	5.44	18.34	15.93	1.09	-	0.05	0.17	-	Caillaud et al. (2009)
Haut Limousin, France	120-140	37.97	4.01	18.81	19.10	0.12	-	-	0.06	-	Caillaud et al. (2009)
Haut Limousin, France	Rock (>140)	39.61	1.49	7.79	36.41	-	-	-	-	-	Caillaud et al. (2009)
Szklary Massif, Poland	4-25	59.26	5.73	7.78	9.88	1.33	-	-	-	-	Kierczak et al. (2007)
Szklary Massif, Poland	25-32	52.28	4.33	10.47	15.89	0.84	-	-	-	-	Kierczak et al. (2007)
Szklary Massif, Poland	Rock > 32	38.99	1.00	9.37	38.15	0.17	-	-	-	-	Kierczak et al. (2007)
Nove Dvory, Czech Republic	Few meters	41.38	2.30	7.86	31.95	1.88	0.16	0.02	0.07	0.02	Quantin et al. (2008)
Ussangoda, Sri Lanka	0-15	41.00	12.20	38.30	0.94	-	0.04	0.45	1.43	0.17	Vithanage et al. (2014)
Yudhaganawa, Sri Lanka	0-15	33.20	7.29	32.20	2.98	-	0.16	0.66	1.20	0.11	Vithanage et al. (2014)
Indikolapelessa, Sri Lanka	0-15	45.30	12.70	17.50	4.22	-	0.43	0.76	1.55	0.11	Vithanage et al. (2014)
Ginigalpelessa, Sri Lanka	0-15	39.10	7.92	23.30	2.98	-	0.12	0.27	0.49	0.10	Vithanage et al. (2014)

mineral associations, four different types of serpentinites have been recognized (oolitic serpentinite, fibrous serpentinite, mesh-like serpentinite and micaceous serpentinite) in the Indikolapelessa outcrop (Dissanayake and Riel, 1978). Further, high range of Ni was found in in spinels whereas Cr and Mn were mainly found in the chrome spinels and limonitic materials, respectively (Dissanayake, 1982). A recent study on soil geochemical mapping at Indikolapellessa deposit found a significant difference in Fe, Ni, Cr, Mn, Mg and Ca/Mg ratio between the serpentinite soil and non-serpentinite soils, demarcating a geo-vegetation boundary in Indikolapellessa deposit (Hewawasam et al., 2014). Lack of macronutrients, high concentration of heavy metals, shallow soil thickness and little fraction of clays and silts have been limited to a certain plant species growth on serpentinite outcrop at Indikolapelessa (Hewawasam et al., 2014). From a geochemical point of view, upper

horizon of the serpentinite weathering profile has been studied in detail in Sri Lanka. Vithanage et al. (2014) have studied major and trace metal concentrations in upper soil horizons of for different serpentinite outcrops (Table 1 and 2), Ussangoda, Yudhaganawa, Ginigalpelessa and Indikolapelessa. In addition, metal bound fractions for Mn, Ni and Cr have been successfully studied in those locations. The reported metal bound fractions for each metal from greatest to least are as follows: (1) Mn: Fe and Mn oxides bound > Residual > Organic matter bound > Exchangeable > Carbonate bound, (2) Ni: Residual > Fe and Mn oxides bound > Organic matter bound > Exchangeable > Carbonate bound and (3) Cr: Residual > Organic matter bound > Fe and Mn oxides bound > Exchangeable > Carbonate bound (Rajapaksha *et al.*, 2012; Vithanage et al., 2014). However, other soil profiles developed on these ultramafic rocks in different locations have not been studied yet.

REMARKS

Serpentinite outcrops globally and locally have exceeded the concentration of heavy metals such as Mn, Co, Ni and Cr than in earth's crust. As a result, living organisms such as plants and wildlife in surrounding areas can be directly or indirectly affected due to the high concentration of bioavailable and exchangeable fractions of the heavy metals. Mineral scale investigations along the serpentinite weathering profile revealed that composition of weathering products and surroundings vary from location to location. Further, metal bound phases and metal bearing minerals need to be investigated in detail in Sri Lankan serpentinite catena.

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