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Ecological implications of pedogenesis and geochemistry of ultramafic soils in Kinabalu Park (Malaysia)

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ABSTRACT

In Sabah, Malaysia, ultramafic rock outcrops are widespread (totalling 3500 km^2, one of the main outcrops in the tropical zone), and predominantly of the peridotite type. However, strongly serpentinised peridotite is also locally common, particularly along fault lines in the Mt. Kinabalu area. This study aimed to determine the extent of chemical variation in ultramafic soils in relation to the degree of serpentinisation and the weathering intensity, and consequent potential ecological implications linked to resulting soil chemical fertility. It was hypothesized that young soils and soils derived from bedrock with a significant degree of serpentinisation strongly differ from typical Geric Ferralsols and result in soil chemistries with more adverse properties to plant life (*e.g.* low availability of the essential nutrients N, P, K and Ca and high concentrations of potentially phytotoxic Mg and Ni). Ultramafic soil diversity linked to the age of the soil or the degree of serpentinisation would thus be a main factor of plant diversity and distribution. The diverse topography of Kinabalu Park (ultramafic soils present between 400 and 2950 m asl) has given rise to high pedodiversity with the broad overall ultramafic soil types being: (i) deep laterite soils (Geric Ferralsols); (ii) moderately deep montane soils (Dystric Cambisols) with mor humus; (iii) shallow skeletal soils at high altitude (Eutric Cambisols Hypermagnesic); and (iv) bare serpentinite soils (Hypereutric Leptosols Hypermagnesic) at low altitude (200–700 m asl). Leptosols on serpentinite and Eutric Cambisols have the most extreme chemical properties in the whole Kinabalu Park area both with very high Mg:Ca molar quotients, with either high available Ni (Cambisols) or high pH (Leptosols). These soils host specific and adapted vegetation (high level of endemism) that tolerates geochemical peculiarities, including Ni hyperaccumulators. Geric Ferralsols present far less chemical constraints than Hypermagnesian Cambisols soils to the vegetation and host a tall and very diverse rainforest, not so different than that on non-ultramafic soils. It therefore appears that altitude, soil age and degree of bedrock serpentinisation are the main determining factors of soil properties: the qualifier "ultramafic" alone is not sufficient to define soil geochemical and ecological conditions in the Kinabalu Park area, probably more than in any other ultramafic region in the world.

1. Introduction

1.1. Properties of ultramafic soils

Ultramafic bedrock is part of the upper mantle (peridotite) obducted in continental margins (Searle and Stevens, 1984). Such outcrops are widespread but relatively rare, covering > 3% of the surface of the earth (Guillot and Hattori, 2013). The largest ultramafic regions in the world can be found in temperate (*e.g.* Balkans, Turkey, California) and in tropical environments (*e.g.* New Caledonia, Cuba, Brazil, Malaysia, Indonesia). Southeast Asia has some of the largest tropical outcrops in the world with Borneo and Sulawesi together totalling over 23,000 km^2 (van der Ent et al., 2013; Galey et al., 2017). The rock-type peridotite is made up from magnesium-iron-silicates in the minerals olivine and (ortho)pyroxene (Coleman, 1971). Low-temperature hydration and metamorphism of peridotite leads to serpentinite, usually at the sea floor along tectonic boundaries (such as near mid-ocean ridges) or during continental emplacement (Lewis et al., 2006; Guillot and Hattori, 2013). During serpentinisation, the mineral assemblage is completely altered to metamorphic equivalents, and only chromite usually remains unaltered (Coleman, 1971; Alexander, 2009). Serpentinite rocks contain very high Mg (18–24%) and high Fe (6–9%) but low

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Ca (1–4%) and Al (1–2%) (Alexander, 2004). The total transformation of peridotite to serpentinite needs 14% water and the rock expands by 33% from dense peridotite (3.2–3.3 g cm^3) to less dense serpentinite (2.4–2.6 g cm^3) (Alexander, 2009). This results in fracturing and shearing of the rock, and as such, the weathering properties of serpentinite rocks are dramatically different from peridotite bedrock. All near-surface ultramafic rock is serpentinised to varying degrees, and serpentinite is used to describe rocks containing > 50% serpentine-group minerals (*i.e.* antigorite, chrysotile, lizardite) in which the original (primary, or not metamorphosed) mineralogy is obscured. Ultramafic rock generally itself only contains 0.16–0.4% nickel (Butt, 2007) however these initial concentrations increase significantly during surface weathering in humid tropical climates, resulting over the long term, in nickel laterite soils (Echevarria, 2018). Such nickel-enriched ultramafic soils are a major target for the nickel and cobalt mining industries, particularly in tropical settings such as in Cuba (Roqué-Rosell et al., 2010), Brazil (Colin et al., 1990), Indonesia, the Philippines and New Caledonia (Butt, 2007; Fan and Gerson, 2011).

Properties commonly shared among ultramafic soils include high iron (Fe) and magnesium (Mg) concentrations and low aluminium (Al) concentrations, relatively high concentrations of chromium (Cr), cobalt (Co) and nickel (Ni), high magnesium-to-calcium (Mg:Ca) quotients in the exchange complex and low concentrations of phosphorus (P) and potassium (K) (both total and extractable). In ultramafic laterites (*i.e.* Ferralsols), some of these features might be less strongly marked because intense weathering has erased the fingerprint of geochemical peculiarities: *i.e.* a higher aluminium (Al) concentrations and lower magnesium-to-calcium (Mg:Ca) quotients than in ultramafic Cambisols or Luvisols (Echevarria, 2018).

1.2. Geology of ultramafic outcrops in Kinabalu Park

Ultramafic outcrops cover 3500 km^2 in Sabah (Proctor et al., 1988; Repin, 1998) and 151 km^2 in Kinabalu Park (Fig. 1a). The ultramafic rocks are part of an ophiolite suite which derived from a collision suture between the Kalimantan micro-continent and the Sulu Arc (Imai and Ozawa, 1991) when oceanic lithosphere of the Sulu Sea was obducted (McManus and Tate, 1986). Mount Kinabalu (4095 m) is a granite intrusion dated 7.2 to 7.9 Ma before present (Cottam et al., 2010) and ultramafic outcrops form a 'collar-like' distribution on the mid-elevation around the Kinabalu granite core. In the northern part of Kinabalu Park lies Mount Tambuyukon (2579 m). Of the outcrops in Kinabalu Park, Mount Tambuyukon is the largest (89 km^2), but many small outcrops (< 1 km^2) also exist especially around Mount Kinabalu (Fig. 1b). In the Kinabalu area the most common peridotite is lherzolite, and tremolite-bearing peridotites whereas harzburgite and wehrlite are rare (Jacobson, 1970).

1.3. Pedogenesis and mineralogy of ultramafic soils

Ultramafic bedrock contains on average approximately 0.2% Ni, 0.02% Co, 10% Fe and 0.2% Cr (Butt and Cluzel, 2013). A recent article summarises the main factors involved in ultramafic soil pedogenesis (Echevarria, 2018). In tropical settings, weathering of ultramafic bedrock leads first to secondary phyllosilicates (Cambisols), then to amorphous and poorly-crystalline Fe-Cr-Mn oxides, and finally to crystalline Fe-oxides (Schwertmann and Latham, 1986; Becquer et al., 2006; Echevarria, 2018). In well-drained soils, peridotite minerals (olivine and pyroxenes) weather to form secondary (Fe-rich) minerals (goethite, hematite), and Mg and Si move down the soil profile and accumulate at depth (Latham, 1975b; Trescases, 1975; Proctor, 2003) whereas Fe, Cr and Al are less soluble and remain higher up in the profile. Nickel is also highly leached during pedogenesis, in contrast to other metals, *e.g.* Al (Estrade et al., 2015; Echevarria, 2018). The results are deep red 'laterite' soils consisting of a limonite (Fe-oxide) layer and a saprolite (Mg, Si-rich) layer (Gleeson et al., 2003). Total Cr concentrations are generally very high in the limonite layer. The secondary Fe and Mn oxides are known to be a major sink for Ni because of their high sorption capacity (Becquer et al., 2001), often containing 0.8–1.5 wt% Ni (Fan and Gerson, 2011). The Ni, Mg and Si leached into the saprolite are the main 'ore' mined in the lateritic nickel mining industry, where Ni is embedded in phyllosilicate minerals (Freyssinet

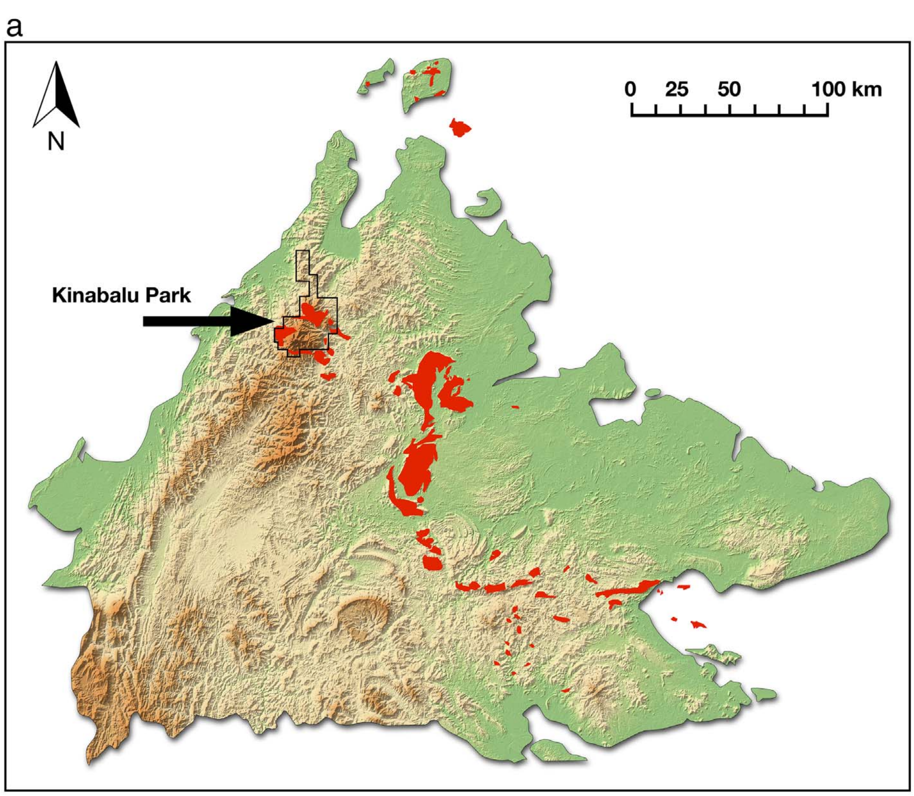

Fig. 1. a. Shaded relief map of Sabah with major ultramafic occurrences (marked in red) totalling approximately 3500 km^2 (van der Ent et al., 2014). b. Geological map of the study area with sampling sites marked (coloured circles). Geology shape files from Robert Hall, Department of Earth Sciences, SE Asia Research Group, Royal Holloway, University of London.