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Editorial

Nickel laterites as sources of nickel, cobalt and scandium: Increasing resource efficiency through new geochemical and biological insights

This special volume compiles papers which were presented at the International Conference on Nickel Geochemical Cycling at the Université de Lorraine in Nancy, France, in October 2018. The conference was hosted by "LabEX Ressources21" headed by Dr. Michel Cathelineau.

Nickel (Ni) laterites comprise regoliths derived from ultramafic bedrock that form under humid tropical climates worldwide. They originate from peridotite and serpentinite bedrock, consisting predominantly of ferromagnesian silicate minerals (Moores, 2011). These soils (Ferralsols) contain economically valuable nickel (Ni) and cobalt (Co) resources (*e.g.* Wilburn, 2012), and in some cases also scandium (Sc), particularly used in the aerospace industry in alloys (Chassé et al., 2017). The decline in Ni sulphide reserves, has led to a growth in Ni production from Ni laterite resources (Taylor, 1995; Mudd, 2009). Currently, Ni laterites represent 60–70% of the Ni resources worldwide (Butt and Cluzel, 2013). This shift from processing high-grade sulphide deposits to low-grade laterite deposits has a number of technological and environmental consequences. Nickel production from laterite ores consumes up to three times more energy compared to process sulphide ores, and as a result it increases the greenhouse gas footprint of this industry (Diaz et al., 1988, 2004; Mäkinen and Taskinen, 2008; Eckleman, 2010). Furthermore, Ni production of over 2 million tons/year produces high quantities of dust along the processing chain and during steel making (INSG, 2018). This may contaminate the atmosphere and presents a health risk (*e.g.* WHO, 2000, Das and Das, 2008, Ekosse, 2008, The Guardian, 2017).

Furthermore, globally, Ni laterites are renowned for hosting high levels of plant diversity with disproportionate amounts of endemism, including plants with specialized adaptations such as Ni or manganese (Mn) hyperaccumulation (Galey et al., 2017). The latter are unusual plants that have the ability to naturally concentrate exceptionally high concentrations of metallic elements into their living shoots (Reeves, 2003; van der Ent et al., 2013a). The most extreme example is the tree *Pycnandra acuminata* growing on Ni laterites in New Caledonia which can accumulate up to 25.74 wt% Ni in its latex (Jaffré et al., 1976).

Nickel in laterites is mainly recovered from the saprolite horizon, the lower part of the laterite profile, which typically hosts 1–3 wt% of Ni. Exploration and processing challenges are the variable vertical and horizontal Ni concentrations and multiple types of Ni hosts (serpentine minerals, clays, Ni hydroxides and silicates, *etc.*). Nickel from laterites is mainly recovered through pyrometallurgy (*e.g.* ferro-nickel smelting) from saprolites, or by hydrometallurgy from oxide horizons (Diaz et al., 1988, 2004; Taylor, 1995; INSG, 2009). In some cases, other valuable metals, including Co or Sc, may be recovered, using hydrometallurgy (Kaya et al., 2017). Emerging approaches to recover Ni from laterites soils is the use of "phytomining" which is an innovative method of growing and harvesting hyperaccumulator biomass to produce bio-ores (van der Ent et al., 2013b; van der Ent et al., 2015a, b).

For more efficient Ni and Co–Sc by-production from the raw material chain, the major questions are: (i) where are these metals located in the laterite profile? (ii) do they vary with Eh and/or pH in the laterite profile, and, thus, depending on the laterite type? (iii) which minerals host the Ni, Co and Sc metals and how are they associated in the different laterite horizons? (iv) is there are possibility for the use of phytomining for Ni and Co? and (v) is there are role of biogeochemical prospecting in locating Sc reserves? In order to increase the resource efficiency through speeding up exploration and processing and optimizing geometallurgical parameters, national and international projects are financing the development of on-line drill core sensors Red-Green-Blue (RGB) camera, X-ray Fluorescence (XRF), visible-near-infrared (VNIR)-short-wave infra-red (SWIR) and Raman spectrometers.

This special volume includes 18 articles on Ni laterites from Spain, Turkey, New Caledonia, Australia, Indonesia and Malaysia. Roughly half of the articles are related to biochemical behavior of Ni, Co and Sc in the context of phyto-technologies, including phytomining, the other half focusses on research on ore characterization in laterite profiles. The sustainability aspects of the Ni mining industry are also covered.

Nickel laterites are generally deficient in essential plant mineral nutrients (phosphorus; P, potassium; K), have major cation imbalances (low calcium; Ca-to-magnesium; Mg molar ratios), and have high concentrations of certain phytotoxic elements, including Ni, Co and manganese (Proctor, 2003). Although these unusual chemical characteristics are well-known, few studies have compared different soil extraction methods on tropical ultramafic soils to better characterize these properties. The work by van der Ent et al. (2019a) provides a case study from the varied ultramafic soils occurring on Kinabalu Park, Malaysia. Some of the world's largest Ni laterite outcrops occur in Indonesia, with 15,400 km^2 in Sulawesi and another 8000 km^2 of ultramafic outcrops in Halmahera (van der Ent et al., 2013a, b). Nickel laterites are frequently biodiversity hotspots such as in Cuba, Borneo, and New Caledonia (Borhidi, 1992; van der Ent et al., 2015a, b; Isnard et al., 2016). The first estimates suggest that hyperaccumulation occurs in less than 0.2% of worldwide plants (Reeves, 2003) and in 1–2% of the ultramafic flora (van der Ent et al., 2015a, b), with over 500 Ni hyperaccumulator plant species known to date (Reeves et al., 2017). However, some areas of the world remain poorly explored, and the article by Lopez et al. (2019) reports on the discovery of 13 Ni and two Co hyperaccumulator plant species from Weda Bay on Halmahera Island in Indonesia. Nearby, on the island of Borneo a new approach called "XRF Herbarium Ionomics" has been used to systematically scan vast

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herbarium holdings (~7300 specimens) which led to the discovery of 28 Ni hyperaccumulator species and 51 Mn hyperaccumulator species (van der Ent et al., 2019b). Plant have also been used as indicators for buried mineralization, and Paul et al. (2019) report on the use of vegetation to probe for Sc at the Lucknow Deposit in Queensland, Australia.

Several articles report on the testing of Ni phytomining systems in the field. The work by Nkrumah et al. (2019a) describes the results of a 'metal farm' in Malaysia where growth performance and Ni yield were tested in *Phyllanthus rufuschaneyi*. In a separate study, the authors assessed different soil amendments to increase Ni uptake in the same metal crop species (Nkrumah et al., 2019b). Cerdeira-Pérez et al. (2019) describe field experiments in Spain, highlighting increases in plant growth after improving soil quality to support rehabilitation of soils affected by quarrying operations. Phytomining (synonymous here with 'phyto-extraction') has also been demonstrated for extracting Ni from contaminated industrial sludges amended with biochar using the hyperaccumulator *Alyssum murale* (Rue et al., 2019). Another study looked at the use of tolerant plants for stabilization of degraded tropical serpentinite quarries and dump sites testing a number of reclamation practices (Quintela-Sabarís et al., 2019). Research undertaken in Brazil (at the Barro Alto and Niquelândia ultramafic complexes) studied Ni stable isotope fractionation between ultramafic soils and Ni accumulator species showed that these plants can modify the Ni isotope composition at the soil-plant interface and the overall cycle of Ni in surface soils (Ratié et al., 2019).

Nickel laterite geochemistry and mineralogy is intensely studied with coupled analytical approaches such as Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS), Raman spectroscopy, Quantitative Evaluation of Materials by Scanning Electron Microscopy (QEMSCAN), X-ray powder diffraction (XRD), XRF. Nickel laterites in New Caledonia were analyzed along a New Caledonian laterite profile for Co and Sc (Ulrich et al., 2019). The authors developed a new method for LA-ICP-MS analysis and suggest that the Sc enrichment at the interface yellow and red laterite could be utilized as a by-production together with Ni and Co. In addition, Teitler et al. (2019) proposed three main factors controlling the distribution of Sc enrichment in laterites derived from mafic and ultramafic rocks (Sc content of the bedrock), the development of intensive goethite formation in yellow limonite, the downward remobilization of Sc into the yellow limonite through dissolution/recrystallization of goethite and partial replacement by hematite. In oxide dominated Ni—Co laterites in Western Australia Putzolu et al. (2019) studied in particularly the Sc and REE enrichment processes. In these deposits, Sc is enriched in the saprolite rather than in the oxide zone. In the latter deposit, Co, hosted by Mn oxyhydroxides, and REEs (except Ce) are enriched in the limonite zone. Bedrock composition and variable serpentinization degrees are found to be responsible for the various levels of metal enrichment.

Muñoz et al. (2019) undertook detailed studies on the mineralogy of the Ni carriers using micro imaging and X-ray absorption spectroscopy (XAS) of a saprolite boulder from a Ni mine New Caledonia. Increasing redox potential (Eh) and decreasing pH are driving forces for Ni enrichment in the latest generation serpentines and the of formation Ni-rich talc-like phases. Farrokhpay et al. (2019) coupled XRF, Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS), QEMSCAN and XRF and outline the difficulty of separating Ni-rich from Ni-poor phyllosilicates in the saprolite horizon as they are intimately intermingled and found Ni associated with goethite in the limonite horizon at the Weda Bay deposit in Indonesia.

Industrial applications of minerals formed during the lateralization process, such as talc (oil drilling, fillers) need pure phases (Kloprogge et al., 1999), which are mainly obtained by synthesis. In order to reach high-quality synthetic products, it is important to study the precursor materials of these minerals also in natural environments. Martin et al. (2019) reviewed the current knowledge on the incorporation of Ni and Co cations in mineral synthesis in the view of applications as mineral fillers, in close comparison with equivalent minerals formed in Ni laterites. At present, the EU finances several projects on on-line analytical sensor developments for drill core analyses for mining and oil industries to speed up exploration and increase the resource efficiency (*e.g.* SOLSA, ANCORELOG, PAIRED-X; www.solsa-mining.eu; https://eitrawmaterials.eu/project/ancorelog/; http://nanoair.dii.unitn.it:8080/paired-x/). In order to obtain reliable analyses of each instrument on drill core surfaces (rough, diamond-sawed), Duée et al. (2019) undertook a systematic study on contrasting lithological materials (different lithologies, different grain sizes and porosities: granite, peridotite, sandstone, breccia) to compare the results of portable XRF, and infra-red spectroscopy with laboratory measurements (XRF, ICP-MS, Raman spectroscopy and XRD).

Finally, Ni laterite mining has been assessed in the context of ecological, socio-economic and political aspects, presenting an interesting case study in New Caledonia, at the Koniambo Mine in the North Province focussing on local community challenges (Kowasch, 2018).

The wide-ranging studies presented in this Special Volume highlight the diverse aspects of research undertaken on Ni laterites globally. Given that the importance of Ni laterites for the commercial production of Ni, Co (and possibly Sc) metals are expected to increase in the future these studies make important contributions to this emerging field. The relatively low-grade properties of Ni laterites, compared to conventional Ni sulphide deposits, calls for innovative methods for efficiently extractable valuable metals. Better insights in the nature of laterite deposits, and their Ni, Co and Sc bearing phases, may lead to enhanced and targeted extraction technologies. As Ni laterites are surface deposits typically mined using strip-mining methods, environmental remediation is a priority concern. The use of phytomining as an approach to both rehabilitate mined out landscapes and extract residual Ni is a particularly promising avenue of research that is likely to lead to implementation.

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