



ORIGINAL PAPER

BEHAVIOR OF NI AND CO IN MINING WASTE (OVERBURDEN) OF POOR LATERITE ORE FROM KŘEMŽE DEPOSIT IN THE MAGNETIC FIELD

**Martin ŠTRBA^{1,2)}, Zdeňka WITTLINGEROVÁ¹⁾, Michal POŇAVIČ²⁾,
František PTICEN²⁾ and Monika PACHTOVÁ¹⁾**

¹⁾ Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague – Suchbát

²⁾ Czech Geological Survey, Klárov 3, 118 21 Prague

*Corresponding author's e-mail: strba@fzp.czu.cz

ARTICLE INFO**Article history:**

Received 7 August 2025

Accepted 25 November 2025

Available online 11 March 2026

Keywords:

Laterite

Nickel

Cobalt

Bohemian Massif

Magnetic separation

Technological treatment of raw material

ABSTRACT

This work presents new results of the pre-processing study of the Ni and Co-poor lateritic raw material from the reserved deposit Křemže in South Bohemia. The proposed technological treatment of the raw material aims to obtaining a concentrate of elements of interest. This step is missing in the present Ni and Co extraction from laterites as the entire amount of the mined rock is being leached. This work focuses on a possible pre-concentrating of elements of interest and facilitating the final metallurgical processes. We carried out experiments involving interconnected pre-processing modes, such as magnetic separation, heating of the raw material, oxidation by ozone, or use of a low frequency supersound. The experiments showed that an appropriate combination of these pre-processing modes can result in a substantial concentration of Ni and Co (from 0.4 to 1.05 wt. % Ni and 0.01 to 0.027 wt. % Co). The incorporation of these pre-processing modes into the technological method of laterite ore processing can reduce total costs of the raw mineral treatment. In addition, it makes it possible to process poorer raw materials whose treatment was previously uneconomic.

INTRODUCTION**CURRENT METHODS OF NI AND CO EXTRACTION FROM LATERITES**

With the development of new technologies, which often require very specific mineral commodities, it is becoming increasingly important for major global players, including Europe, to have certainty of access to these often very specific raw materials. Indeed, they are often dominantly, sometimes even monopolistically, produced by one or a few countries in the world. For this reason, the European Commission has decided to change its current raw materials strategy and attention is now being paid to the study of European deposits and resources of so-called EU critical raw materials. Raw materials which are of major economic importance to Europe, and which are at risk of supply constraints. The list is updated regularly at three-yearly intervals, with the last update taking place in February 2023 (European Commission, 2023).

Although the geological structure of the Bohemian Massif is quite diverse, only a small part of the raw materials from the CRM-2023 list form exclusive deposits with reserves in the Czech Republic. Of European importance are mainly feldspars, coking coal, lithium, tungsten, and manganese, while graphite, fluorite, barite, and germanium are of national importance. Other raw

materials are also potentially promising, but many of them are either difficult to treat or their treatability has not yet been sufficiently studied, such as cobalt and nickel. Cobalt is included in the EU-CRM, while nickel is considered a strategic mineral by the European Commission. Both cobalt and nickel occur in the Czech Republic mainly in laterites of ultrabasic rocks. So far, however, only nickel has been the subject of deposit-geological research and exploration. Cobalt, as a separate commodity, has not been studied so far (Ministry of the Environment, 2024).

Global nickel production has been changing from the production based on the nickel sulphide minerals into the production based on laterite ore deposits. Although nickel and cobalt can be successfully extracted from laterite ores using hydrometallurgical technologies, pyrometallurgy still represents a dominant technology (Dehaine et al., 2021; Meshram et al., 2019). Hydrometallurgy usually cannot compete with pyrometallurgy as the efficiency of the process concerns (Oxley and Barcza, 2013; Stanković et al., 2022). High-pressure acid leaching (HPAL) is a hydrometallurgical technology of nickel extraction from laterites that can compete with pyrometallurgy; however, the input and operating costs are comparable to pyrometallurgical operations, too (Gultom and Sianipar, 2020; Kaya and Topkaya, 2011). Investors prefer to invest their money into

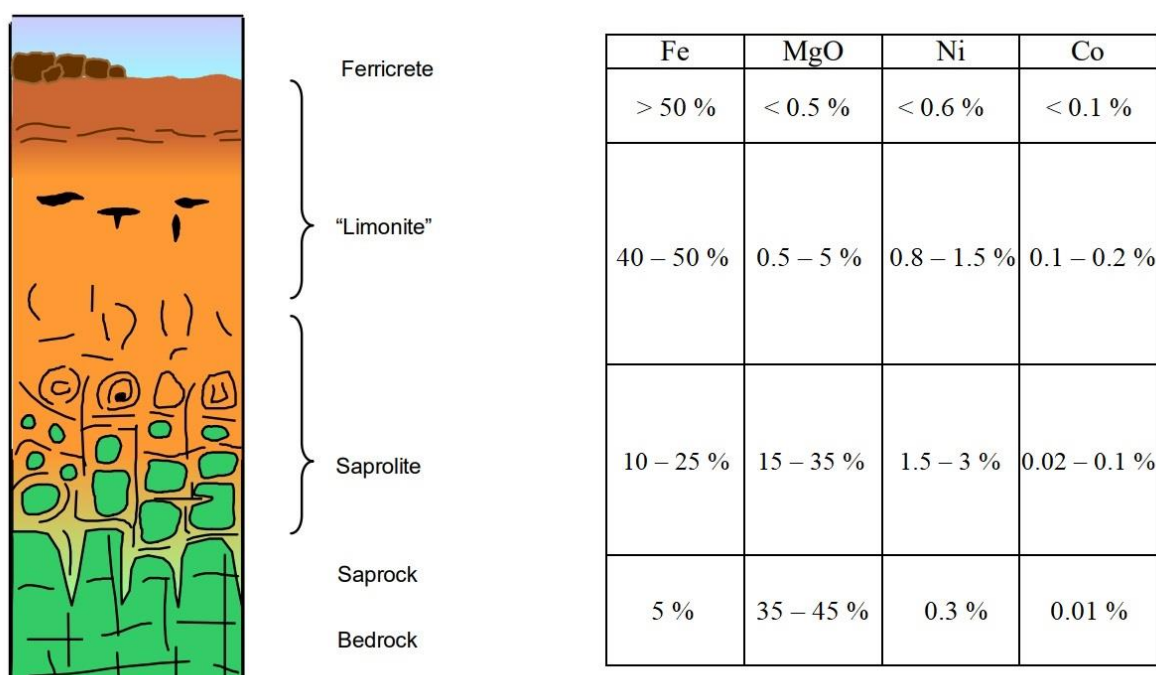


Fig. 1 Scheme of an idealized laterite profile with elemental concentrations in individual zones (Elias, 2002).

proven technologies such as smelters. Many HPAL plants have gone bankrupt or suffered from long start-up delays, huge, unplanned capital expenditures and inability to reach the planned annual production. Therefore, the caution of the investors is understandable. Hydrometallurgical technology of laterite processing should be relatively simple, with significantly lower capital and operation costs compared to HPAL and pyrometallurgy, with a high yield level of Ni and Co (and possibly other valuable elements) and reasonable duration of leaching.

Heap leaching with sulphuric acid mostly corresponds to the description above; however, the duration of leaching is too long (Watling et al., 2011; Oxley et al., 2016). The investigation of the reductive biological heap leaching of laterite ores is in the beginning and literature data are lacking. The catalytic role of bacteria could significantly accelerate the leaching process compared to leaching using sulphuric acid alone. This could represent the most promising approach to the development of a hydrometallurgical process for Ni and Co extraction from laterite deposits (Stanković et al., 2020).

Step temperature acid leaching (STAL) represents the most modern metallurgical technology that will be used for Ni and Co extraction from laterites in the near future. It is based on heating of the input material to an optimum temperature. Leaching at given temperature results in an effective decomposition of silicates and metal liberation. At the same time, the efficiency of the acid during leaching increases due to its reaction with sulphates of Fe (the largest element in a laterite ore) and Al which releases SO_3 gas. This gas is subsequently captured and used to produce new sulphuric acid; therefore, its overall

consumption is lower. The advantage of this method is that it can leach metals from all layers of the laterite profile (STAL technology, 2026).

Leaching is a very reliable and efficient method that is used on all laterite deposits in the world (Butt and Elias, 2003). Whether it is leaching of the limonite (Chang et al., 2016) or saprolite (Komnitsas et al., 2019) layer of the laterite horizon (Fig. 1), the entire volume of the extracted rock is always leached. The technological pretreatment of lateritic rock in a magnetic field before the actual leaching with sulphuric acid or bacteria is completely missing in the literature. It is based on reduction of the volume of the extracted rock and distribution of the elements of interest into concentrates based on magnetic susceptibility. The solubility of the yielded separates at leaching increases after pre-heating to the temperature of about 600–800 °C.

The essence of the technological treatment of the rock is to obtain concentrates of the elements of interest. This step is lacking in the present extraction of Ni and Co from laterites, as the whole volume of the mined rock is leached. This work focuses on the possible pre-concentration of the elements of interest and facilitating and streamlining the final metallurgical processes.

This part of technological investigation of material from the Fe, Si-rich upper part of the laterite profile from the Křemže surroundings aimed to find out how the individual elements of interest, i.e. Cr, Mn, Fe, Co, Ni and Zn, behave in the magnetic field of different intensities on different parts of magnet matrix (coarse, fine). Ideally, the technological works should result in acquisition of concentrates of the elements of interest, which would then be

Table 1 Distribution of particle size fractions from individual localities by percentage.

Křemže laterites		mass fraction (%)					
Location	< 0.1	0.1 – 0.25	0.25 – 0.5	0.5 – 1.0	1.0 – 2.0	>2.0	sum
Perk	16.73	10.22	10.98	11.64	17.55	32.88	100
Červený Kopec	20.06	10.06	13.08	10.96	16.68	29.16	100
Bohouškovice	15.08	12.45	12.67	12.84	18.20	28.76	100

metallurgically processed. Although this is primarily a nickel and cobalt deposit, other metals should also be of interest, as well as elements such as cerium (in Ce-monazite) and zirconium (in zircon). The use of the non-magnetic light fraction (quartz, clay minerals) is also envisaged, which, as part of the comprehensive use of the raw material, will have applications in the construction industry and possibly in agriculture. The use of these minerals will be the subject of a follow-up study.

In the case that the deposit would be mined, which currently appears unfeasible, this upper part would be considered as waste material. The trend in current and future mineral extraction is a waste-free economy. This means that even the poor parts of the deposit, which would have been previously classified as waste with no further use, are now viewed as raw material (Lottermoser, 2011). In this work, technological pretreatment of the raw material in magnetic field was carried out, as a representative of environmentally friendly options to concentrate the elements of interest. Subsequent research will include the potential use of the remaining raw material.

In this work, the technological procedures performed on the finest fraction resulting from crashing and sieving of the whole raw material, i.e. the particle size <0.1 mm, are described. This fraction makes up 15–20 % of the total volume of the raw material (Table 1).

KŘEMŽE NI-LATERITE DEPOSIT

The Křemže Ni-Co ore deposit is bound to serpentinite, which was formed by alteration of the original ultrabasic rocks - olivine-pyrogenic peridotites and probably pyroxenites. Both Ni, and Co are natural components of each serpentinite (Ni from 0.1 to 0.5 %), as they partly represent Mg^{2+} in olivine in peridotites. Depositional accumulation occurs only by supergene processes during lateritic weathering of serpentinite. Lateralization produces not only clay minerals of the montmorillonite group (montmorillonite, β -kerolite, saponite, nontronite), but also silicification by cryptocrystalline modifications of quartz (which can be a complication for mining), iron migration and the so-called "white weathering" - chloritization of biotite, formation of magnesite and talc (these are not widespread in the Křemže massif).

Lateralization took place in the Tertiary (Neogene) under subtropical climate conditions. The depth of lateralization varies, with the main bodies sporadically exceeding 30 m, rarely exceeding 10 m

on minor bodies, and fresh serpentinite extending all the way to the surface on some minor bodies.

Nickel is bound in the laterites of the Křemže deposit in the form of Ni-hydrosilicates (garnierite, pimelite, schuchardite, nepite, rewdinskite, saponite) or adsorbed to clay minerals. In contrast, cobalt is bound together with Mn oxides and hydroxides in asbolane. Thus, from a technological point of view, there are two types of raw material: Ni-hydrosilicates and Mn oxo-hydroxides.

At the Křemže deposit, attention has so far been paid only to the exploration of Ni ores, exploration for cobalt has never been directly focused on (Daler et al., 1970). A total of 5,641 kt of prospected reserves with an average grade of 0.53 % Ni, representing almost 30 kt of Ni metal, have been recorded at the deposit. The Co content was monitored in only part of the samples. From the analyses of the ore deposits, the Ni:Co ratio is 1:0.039, so we can estimate the amount of, Co in the most recently recorded Ni reserves to be approximately 1,170 t of metal.

Similarly, to other world laterite deposits, the laterite deposit at Křemže is vertically zoned. On the basis of the analysis of the documentation of older exploration works, an ideal profile of the laterites has been constructed: 1) fresh serpentinite, 2) zone of firmly weathered serpentinite, 3) zone of brownish-green weathering, 4) zone of red weathering, 5) Quaternary sediments, including displaced weathering (Gabriel, 1988).

The zone of **brown-green weathered rock** is of significance from the deposit-geological point of view. It is the strongest layer (up to 30 m) and the most important deposit location; Ni concentration occurs here. The main component of the weathering consists of clay minerals from the montmorillonite group, as well as veins of Ni-hydrosilicates, siliciphytes, opals and white weathering products - magnesite, talc, kacholong, asbestos, β -kerolite, chlorites, etc. (Pulzová et al., 1958).

In the overburden of this position there is a **red zone**, the color of which is indicated by the accumulated Fe oxides and hydroxides. This band is rich in Si, but poor in most other elements (including Ni) that have been transported to lower bands. This deposit is weathered to a loose state in places, but the use of this deposit is not envisaged in the eventual mining of the deposit. However, the bulk fraction of this deposit in particular may have exceptional potential due to its relatively high Ni, and Co content. For this reason, in this paper we study the technological treatability of this particular deposit.

Table 2 Concentrations of selected elements in the bulk rock from Perk, Červený Kopec and Bohouškovice. Three independent measurements, their average, standard deviation, and variation coefficient are presented. Median of content of selected elements (n=15).

Sample name	Concentration of selected elements (wt. %)		
	Si	Σ	var. coef
Perk – bulk rock	41.6582	1.0025	2.41
Červený Kopec – bulk rock	37.2926	0.7133	1.91
Bohouškovice – bulk rock	40.2520	0.5784	1.44
	Cr	Σ	var. coef
Perk – bulk rock	0.0892	0.001181	1.32
Červený Kopec – bulk rock	0.0924	0.001071	1.16
Bohouškovice – bulk rock	0.0745	0.000927	1.24
	Mn	Σ	var. coef
Perk – bulk rock	0.0329	0.0001105	3.36
Červený Kopec – bulk rock	0.0658	0.0001233	1.87
Bohouškovice – bulk rock	0.0368	0.0001003	2.73
	Fe	Σ	var. coef
Perk – bulk rock	3.1378	0.03665	1.17
Červený Kopec – bulk rock	4.8543	0.03448	0.71
Bohouškovice – bulk rock	3.3908	0.02435	0.72
	Co	Σ	var. coef
Perk – bulk rock	0.0041	0.000356	8.68
Červený Kopec – bulk rock	0.0122	0.000589	4.83
Bohouškovice – bulk rock	0.0069	0.000510	7.39
	Ni	Σ	var. coef
Perk – bulk rock	0.0398	0.001987	4.99
Červený Kopec – bulk rock	0.2127	0.003709	1.74
Bohouškovice – bulk rock	0.0595	0.001780	2.99
	Zn	Σ	var. coef
Perk – bulk rock	0.0074	0.000510	6.89
Červený Kopec – bulk rock	0.0089	0.000616	6.93
Bohouškovice – bulk rock	0.0045	0.000245	5.44

METHODS

Between 13 and 23 kg of lump rock material was collected at each site. This input material was crushed in two stages on a Retsch BB 300 jaw crusher. This was followed by sieving of the crushed rock on sieves with sieve opening size of 0.1, 0.25, 0.5, 1.0 and 2.0 mm, which resulted in six particle size fractions: < 0.1 mm, 0.1 – 0.25 mm, 0.25 – 0.5 mm, 0.5 – 1.0 mm, 1.0 – 2.0 mm and > 2.0 mm. Particle size analysis was performed for these fractions (Table 1).

WD-XRF ANALYSIS OF SIEVED SAMPLES

A Rigaku ZSX Primus IV X-ray fluorescence spectrometer was used for WD-XRF analysis. The WD-XRF spectrometer works by irradiating the sample with incident X-rays. The fluorescence emanating from the sample is measured using a wavelength dispersive detection system. This uses analyzing crystals to split the fluorescence X-rays into individual elemental wavelengths. The WD-XRF provides a high-resolution, low-background spectrum for accurate determination of elemental concentrations (Institute of Materials Science, University of Connecticut).

The following international standards were used for analyses of sieved samples: Kosov Shale, GeoPT44, GeoPT44A, GeoPT40, GeoPT40A, DBC-1, OU 6, OU 1, OU 7, SdaR L2, JB-3, GeoPT28, SBC1, ZWC 382, GeoPT46, GeoPT46A, GeoPT52, 122-CG-2-SBC8 and Geo PT53.

ANALYSIS OF INPUT TECHNOLOGICAL FRACTIONS

First, the concentration of selected elements in bulk rocks from all three sites was determined by ED-XRF analysis (Table 2).

Table 2 shows that Si is negatively correlated with Fe in all three samples. The material from Červený Kopec is the poorest in Si and, conversely, the richest in all the metals studied.

Because of the different concentrations of Fe vs. Si, Ni and Co, two types of ore were distinguished. **Type 1** includes ore from Perk (1a) and Bohouškovice (1b), type 2 is represented by ore from Červený Kopec. **Type 2** is characterized by a high Fe₂O₃ and MgO content (ranging from 4.5-17 %). Compared to the previous type, this layer has a higher Ni, Co and Cr content and, unlike type 1, these elements are probably bound only by Fe and Mn oxohydroxides.

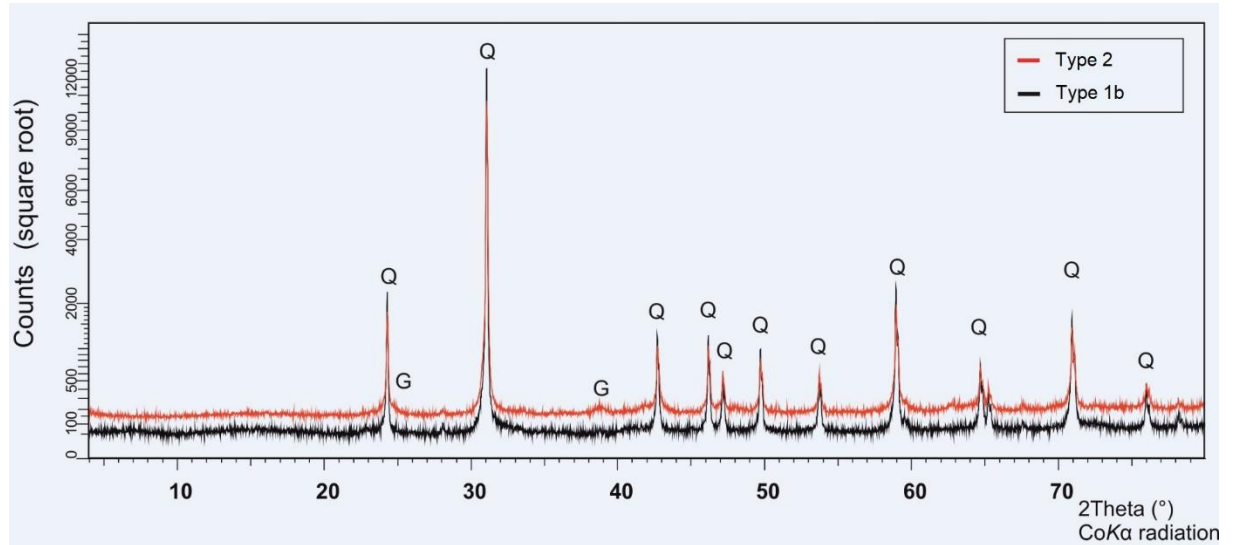


Fig. 2 Comparison of powder X-ray diffraction patterns of ore type 2 and ore type 1b (Q – quartz, G – goethite/hematite).

Table 3 Concentrations of the selected elements in the sieved fractions compared to the concentrations in the total rock for the different ore types. Elevated concentrations (yellow boxes) and more than doubled concentrations (orange boxes) are shown in color.

Ore type	Concentration of selected elements (wt. %)					
	Cr	Mn	Fe	Co	Ni	Zn
TYPE 1a						
Bulk rock	0.0892	0.0329	3.1378	0.0041	0.0398	0.0074
< 0.1 mm	0.1311	0.0965	4.7556	0.0086	0.0613	0.0036
0.1 – 0.25 mm	0.1567	0.0444	2.7583	0.0038	0.0368	0.0037
0.25 – 0.5 mm	0.0888	0.0355	2.5551	0.0024	0.0310	0.0038
0.5 – 1.0 mm	0.0512	0.0234	2.3972	0.0040	0.0325	0.0024
1.0 – 2.0 mm	0.0940	0.0158	2.6272	0.0046	0.0372	0.0031
TYPE 2						
Bulk rock	0.0924	0.0658	4.8543	0.0122	0.2127	0.0089
< 0.1 mm	0.1559	0.1312	9.0094	0.0157	0.4023	0.0100
0.1 – 0.25 mm	0.1906	0.0791	5.8347	0.0078	0.2260	0.0057
0.25 – 0.5 mm	0.1090	0.0614	4.9088	0.0070	0.1846	0.0051
0.5 – 1.0 mm	0.0767	0.0454	4.6061	0.0082	0.1612	0.0059
1.0 – 2.0 mm	0.0760	0.0343	4.2185	0.0093	0.1499	0.0061
TYPE 1b						
Bulk rock	0.0745	0.0368	3.3908	0.0069	0.0595	0.0045
0.1 mm	0.1459	0.1036	5.0597	0.0080	0.1090	0.0120
0.1 – 0.25 mm	0.1098	0.0490	3.5755	0.0018	0.0738	0.0032
0.25 – 0.5 mm	0.0632	0.0316	2.9293	0.0019	0.0554	< LOD
0.5 – 1.0 mm	0.0436	0.0229	2.7130	0.0005	0.0436	0.0028
1.0 – 2.0 mm	0.0787	0.0184	3.0641	0.0028	0.0491	0.0036

Mineralogical composition of samples was studied by powder X-ray diffraction (PXRD). The diffraction data were collected using the Bragg–Brentano geometry on a Bruker D8 Advance diffractometer equipped with a Lynx Eye XE detector and Soller slits (2.5°) in the primary and secondary beams. CoK α radiation was used. The samples were milled in McCrone micronizing mill for 7 minutes in ethanol. A side loading technique was used for preparation of the samples. Diffraction data were

collected in the angular range of 4–80° of 2 θ with a step of 0.015° for 1 s per step. A qualitative phase analysis was performed using the DIFFRAC.Eva software (Bruker AXS, 2015) and the PDF-2 database (Gates-Rector and Blanton, 2019).

PXRD has revealed quartz as a major phase in both samples. Hematite/goethite also was detected in **ore type 2** sample as a minor phase. Traces of kaolinite/chlorite were observed in **ore type 1b** (Fig. 2).

WD-XRF analysis of all sieved fractions on both ore types followed to confirm the assumption that particle size fundamentally affects the distribution of the elements of interest. It was confirmed that Cr, Mn, Fe, Co, Ni and Zn are concentrated in the two finest particle size fractions (Table 3).

It turns out, that the particle size plays a crucial role in metal concentration. The highest concentration, in many cases twice as high compared to the bulk rock, was determined in two finest fractions (< 0.1 and $0.1 - 0.25$ mm). By contrast, the coarser fractions show similar or lower metal concentrations compared to the bulk rock. Iron is only enriched relative to the bulk rock in the finest fraction, while its concentrations in the other fractions are similar or lower.

It was confirmed that sieving to appropriate particle size represents a very efficient way of initial concentration of certain elements of interest, in this case metals. The highest concentrations were determined in the finest fraction of < 0.1 mm. This fraction was subsequently subjected to further technological treatment.

MAGNETIC SEPARATION

Technological treatment of laterite from the Křemže deposit in this study focuses only on the finest sieved fraction < 0.1 mm. This fraction is so fine that it cannot be effectively separated dry on a magnetic belt separator. This is due to the presence of very fine particles of non-magnetic minerals which form clusters around the magnetic particles and can either reduce their magnetic susceptibility or contaminate the magnetic fraction.

Fine material with particle size < 0.1 mm is preferably treated wet. Suspension magnetic separators are used for this purpose. A Sollau magnetic separator, type MX-L, was used for these technological tests. The principle of the separation is that from one side, the suspension is fed under pressure by a hose to the so-called magnet matrix with the help of a pump. The matrix consists of fine metal (mostly steel) fibers that are magnetizable in the magnetic field. The magnetic minerals from the suspension are trapped on the matrix fibers and the non-magnetic fraction of the suspension passes through a hose from the other side of the matrix, where it is subsequently captured. After the separation, the matrix is removed from the magnetic field. The magnetic fraction is washed out from the matrix by water pressure. The process results in two suspensions, one containing magnetic minerals and the other non-magnetic ones.

It is advantageous when the magnitude of the magnetic induction can be selected. The Sollau magnetic separator allows selecting of the magnetic induction magnitude from 0.15 to 1.2 T. These magnetic induction limits of the Sollau magnetic separator, represent well the separation under weak and medium magnetic induction. Unfortunately, separation at high values of induction (1.9 T) is

missing in the study because a separator that allowed separation at such high values was not available for this research.

It is also possible to select particle size of the matrix between fine, medium, and coarse. The wet magnetic separation should be repeated because the suspension is driven under pressure by a pump, and the magnetic fraction can be torn down to the non-magnetic one (Ptíčen and Zítka, 2018). This contrasts with the dry separation, where the material moves in a thin layer slowly by a belt.

RESULTS

The aim of the magnetic separation was to determine and describe behavior of the metals of interest in low and medium intensity magnetic field. Ideally, the separation should yield concentrates of the metals in the magnetic or non-magnetic fraction, thereby reducing the volume of the raw material before subsequent leaching. The suspension for each magnetic separation step was prepared from 50 g of ground rock, 1 liter of water at a temperature of $21\text{ }^{\circ}\text{C}$ and 5 ml of water glass (water solution of Na_2SiO_3), which is used to disperse the material in suspension. The suspension was mixed for 1 minute before separation.

Magnetic separation was performed on all three samples collected. Specifically, the separation was performed on a coarse matrix, first in a weak magnetic field with a magnetic induction of 0.15 T, and then in a medium magnetic field with a magnetic induction of 1.2 T. Finally, the pre-treated samples heated to $130\text{ }^{\circ}\text{C}$ for 12 hours were separated in a medium magnetic field with a magnetic induction of 1.2 T (Fig. 3). This pretreatment was used because it was very effective in our other studies (with other ore types) for metal release. Both the fractions resulting from the separation and the unseparated input material were analyzed by ED-XRF.

Figure 3 shows that majority of metals, specifically Cr, Mn, Fe and Zn, concentrate in magnetic fractions at high induction. Cobalt, for which the highest concentrations are measured in the non-magnetic fractions, exhibits the opposite behavior. A specific behavior is seen for Ni, which apparently does not concentrate in any of the fractions. Figure 3 further shows that the laterites from the different mine fields differ slightly in the measured elemental concentrations; however, their behavior in the magnetic field is the same. For this reason, we show further results from ore type 2.

First, separation of the untreated fraction < 0.1 mm was performed at a low magnetic induction of 0.15 T. For comparison, the same material was separated at the highest magnetic induction of 1.2 T achievable on the Sollau magnetic separator (Fig. 4). The concentrations of selected elements in the non-magnetic and magnetic fraction were compared with the concentrations in the non-separated input raw material.

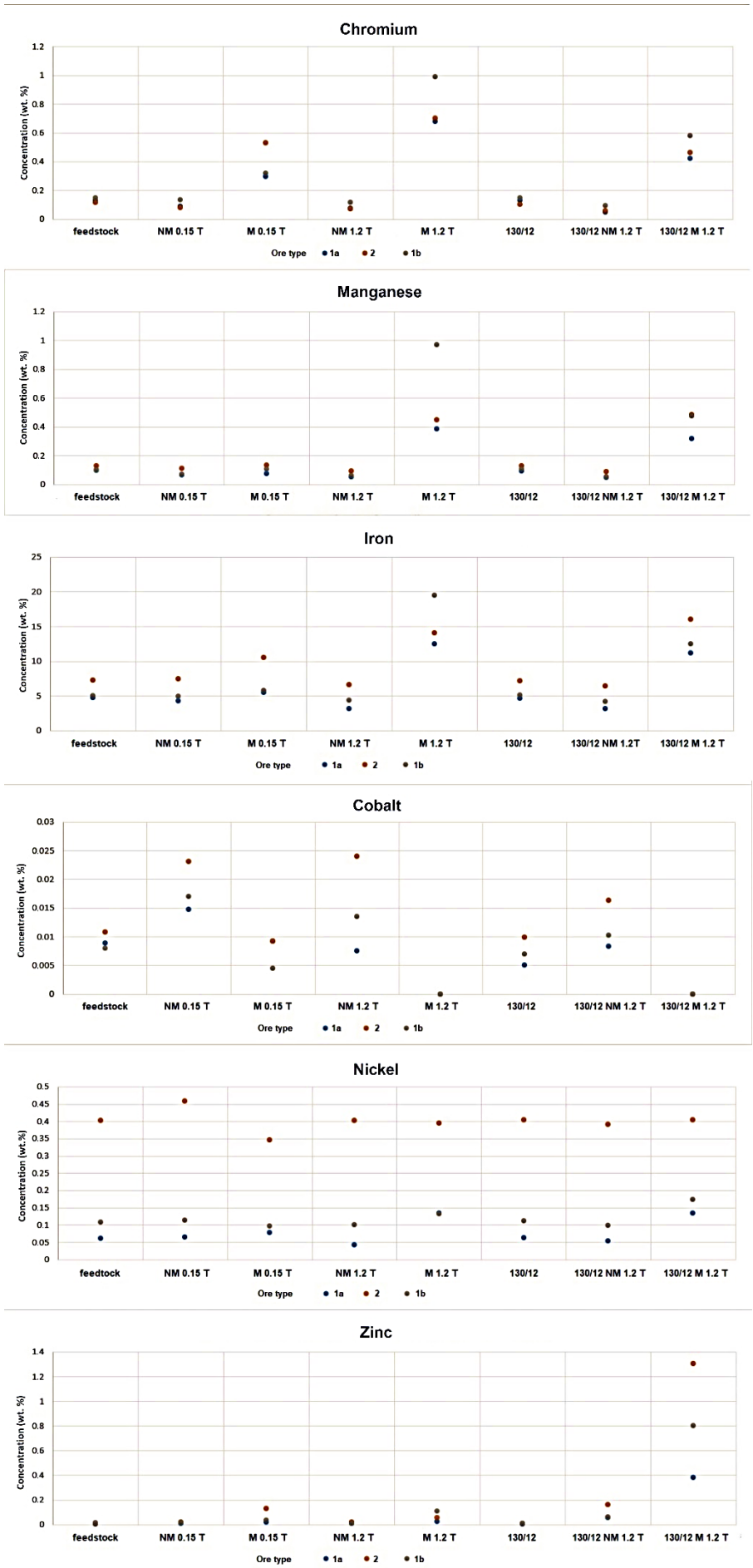


Fig. 3: Concentrations of selected metals in laterites from ore types 1a, 1b and 2, separated on coarse matrix at low (0.15 T) and medium magnetic induction (1.2 T). 130/12 = sample heated to 130 °C for 12 hours.

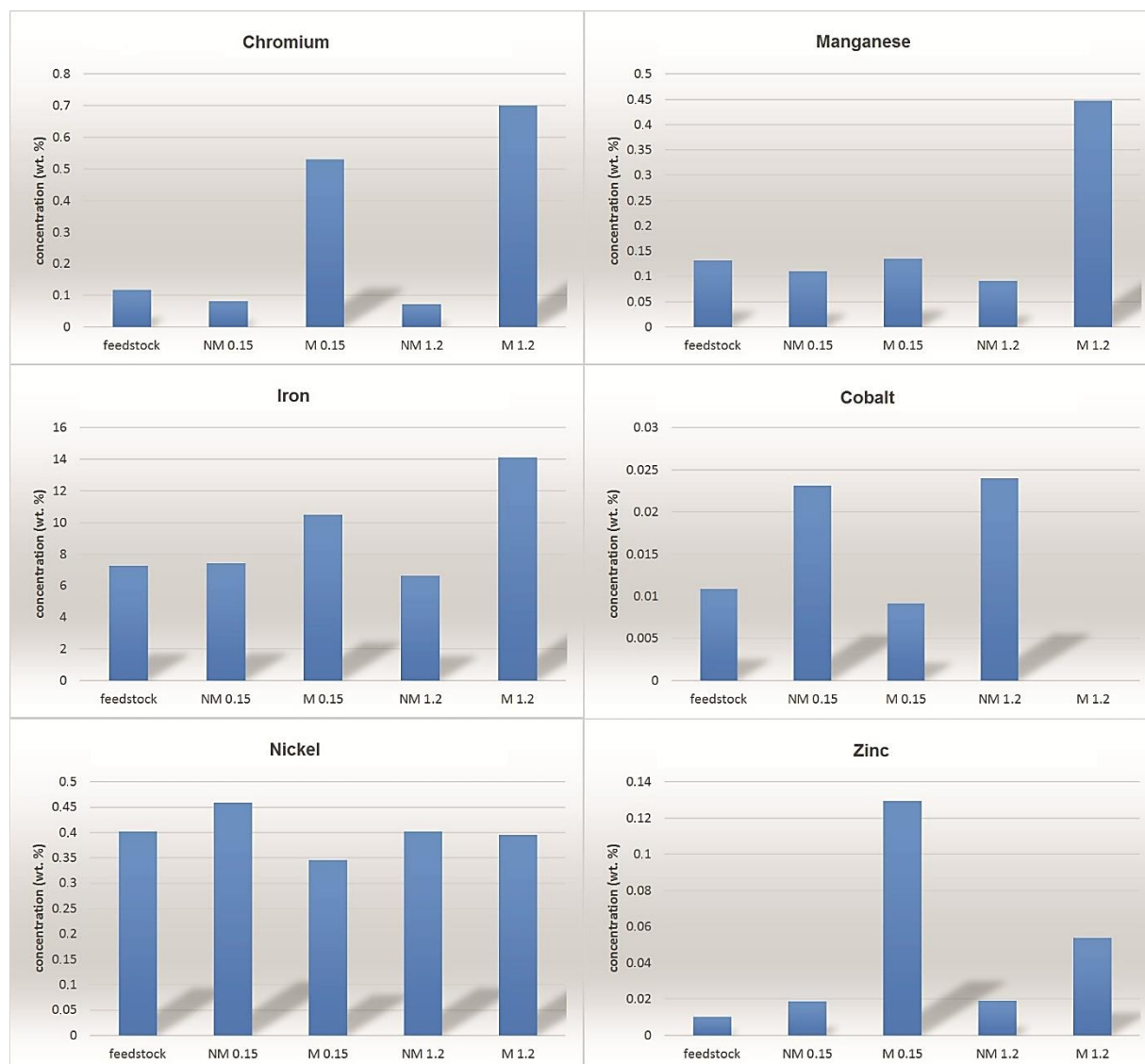


Fig. 4 Comparison of the concentrations of selected metals in the input laterite ore type 2, fraction 0-100 µm, after magnetic separation on a coarse matrix at a weak magnetic induction of 0.15 T and at a medium magnetic induction of 1.2 T; NM = non-magnetic fraction, M = magnetic fraction.

In the next step, the fraction below 0.05 mm was removed by wet sieving from the fraction < 0.1 mm. After that, it was magnetically separated first on a fine and then on a coarse matrix (Fig. 5).

In the last step before the actual magnetic separation, technological pretreatment of the raw material of <0.1 mm particle size, so-called exfoliation, was carried out. The exfoliation of the crushed or ground rock was aimed at releasing minerals of interest which occur in intergrowths with other minerals. The more finely ground the rock is, the less intergrowth it contains. Nevertheless, they are present and can influence, among other things, also magnetic properties of minerals of interest. Distilled water (Tyurnina et al., 2020), or a mixture of water and organic solvent (Beneš et al., 2016), can be used for ultrasonic exfoliation.

For the experiment investigating the efficiency of ultrasound exfoliation, a total of **150 g of laterite ore type 2**, ground to a particle size < 0.1 mm, was used.

The 150 grams were divided into 5 parts of 30 grams each, and each of the 5 parts was mixed in 1 l of distilled water. Each part was successively placed in an ultrasonic cell and exposed to hard ultrasound at a frequency of 20 kHz and power of 100 W for 3, 6, 9, 12 and 15 minutes.

After different duration of exposure to ultrasound, each part was separated in suspension using a Sollau magnetic separator on a fine matrix at a weak magnetic induction of 0.5 T. In addition, laterite ore untreated by ultrasound (input material) was also separated. All suspensions for magnetic separation contained 30 g of laterite, 1 l of distilled water and 5 ml of water glass. The aim of the experiment was to demonstrate that the percentage of the magnetic fraction increases with the increasing duration of exposure to ultrasound (Table 4).

From Table 6 it follows, that the hypothesis that laterite can be exfoliated by ultrasound was confirmed, as shown by the increasing yield of magnetic fraction

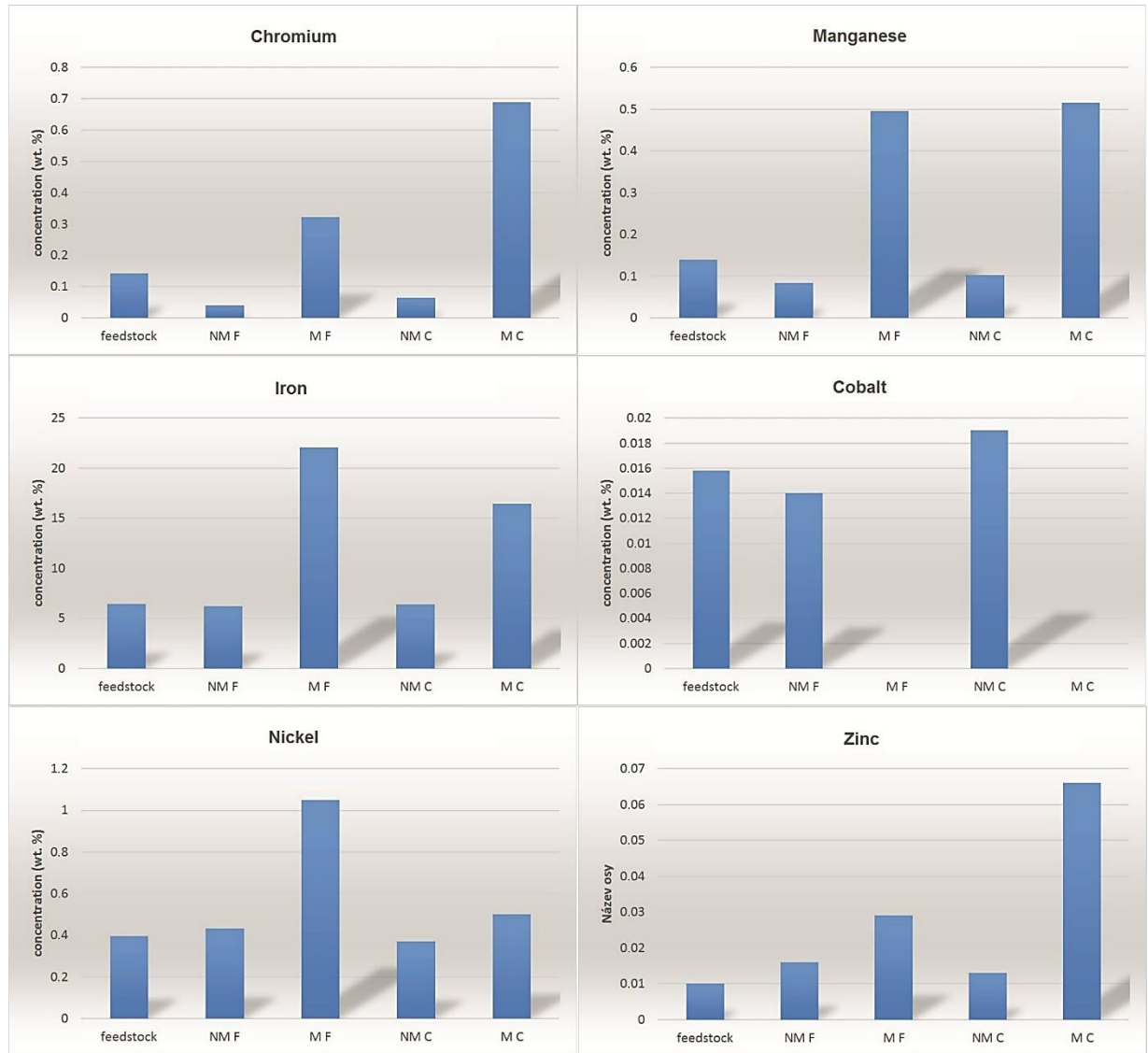


Fig. 5 Comparison of concentrations of selected metals in input laterite ore type 2, fraction 0-50 μm , after magnetic separation on fine and coarse matrix at a medium magnetic induction of 1.2 T; C = coarse matrix, F = fine matrix, NM = non-magnetic fraction, M = magnetic fraction.

Table 4 Correlation of magnetic fraction content with the length of ultrasound exposure of laterite with particle size <0.1 mm.

U/S 20 kHz (min)	laterite (g)	mag. fraction (g)	mag. fraction (%)
0' (input)	30	1.925	6.42
3'	30	2.052	6.84
6'	30	3.249	10.83
9'	30	3.447	11.49
12'	30	3.587	11.96
15'	30	3.617	12.06

with longer exposition in ultrasound cell. This correlation is shown graphically in Figure 6.

In addition to degradation by exposure to ultrasound at a frequency of 20 kHz for 15 minutes, the sample was degraded by heating to 130 °C for 12 hours and by exposure to ozone (O_3) for ten minutes. A comparison of these three methods of degradation is shown in Figure 7.

DISCUSSION

After the first part of the magnetic separation (Fig. 4) in weak field (0.15 T) and then medium field (1.2 T), a strong Cr enrichment compared to the input raw material can be observed in both magnetic fractions (0.5008 and 0.7015 wt. %, respectively). By contrast, non-magnetic fractions are slightly depleted compared to the input (0.0820 wt. % and

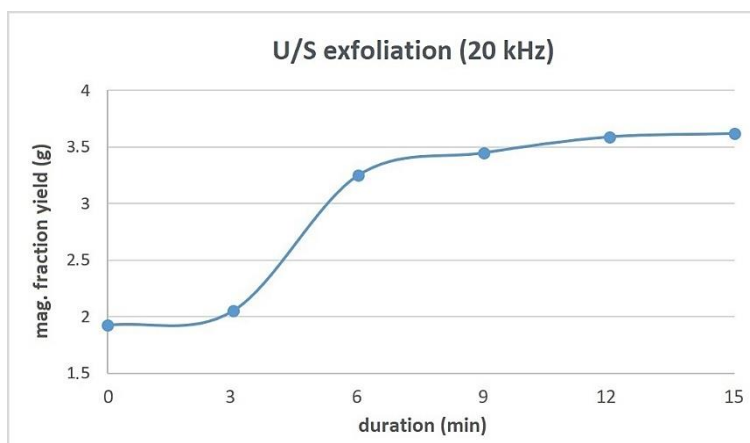


Fig. 6 Increasing yield of the magnetic fraction with increasing length of laterite exposure to ultrasound. Ore type 2, fraction 0-100 μm .

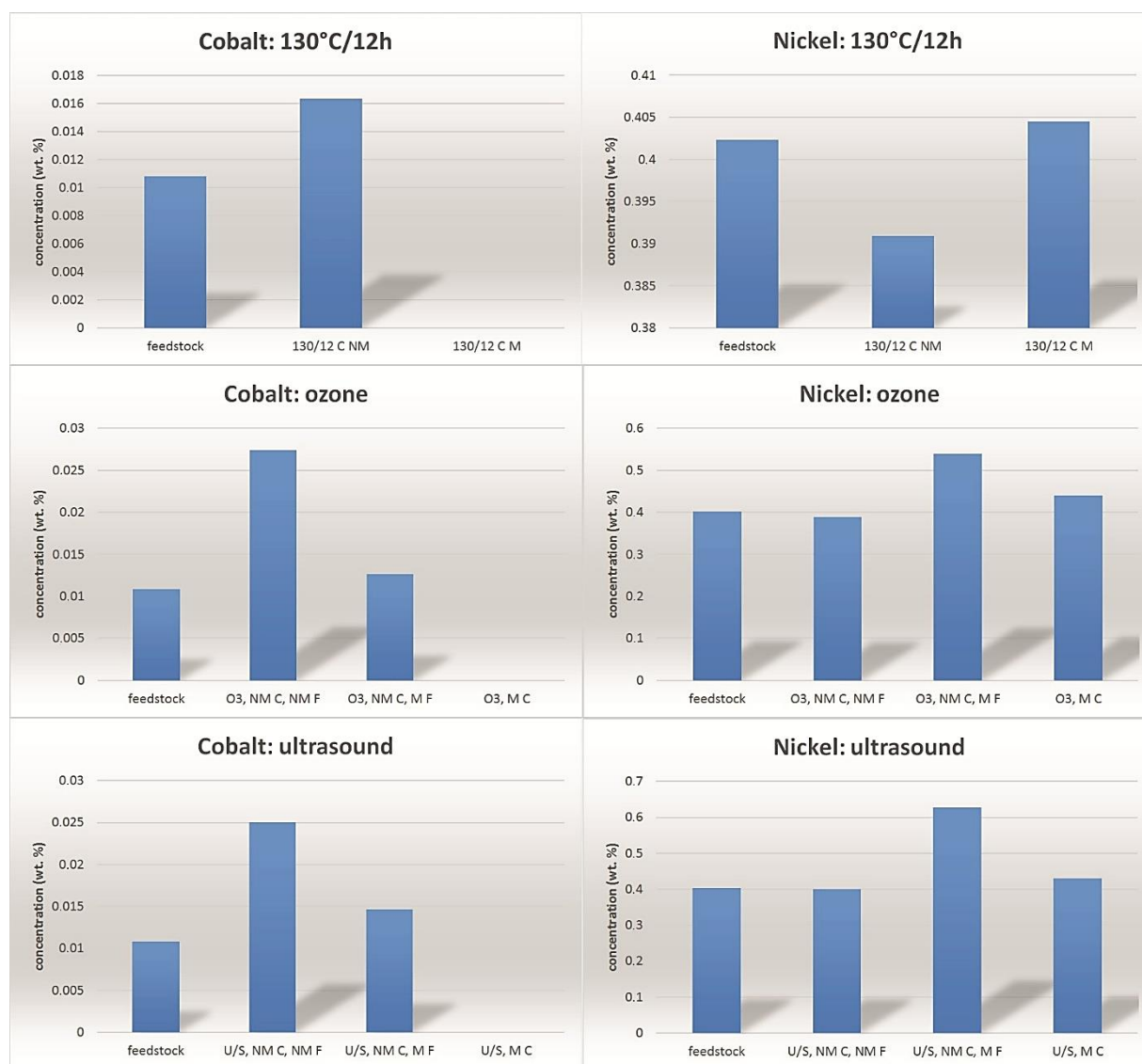


Fig. 7 Comparison of concentrations of selected metals in the feedstock of type 2 laterite ore, fraction 0-100 μm , after magnetic separation on fine and coarse matrix at a medium magnetic induction of 1.2 T after degradation by heating, ozone, and ultrasound; C = coarse matrix, F = fine matrix, NM = non-magnetic fraction, M = magnetic fraction.

0.0709 wt. %, respectively). Manganese shows similar behavior, however, there is much larger difference in concentration between magnetic fraction at weak induction (0.1350 wt. %) and medium induction (0.4478 wt. %). Iron has a slightly higher concentration in the non-magnetic fraction at weak induction than in the input (7.4240 wt. % and 7.2464 wt. %, respectively). Conversely, Zn is concentrated much better in the magnetic fraction at weak induction (0.1293 wt. %) compared to medium induction (0.0538 wt. %). Behavior of Ni and Co is very specific. As for Ni, there was no concentration in either non-magnetic or magnetic fraction. Its distribution is uniform within the fractions. It is very weakly concentrated in the non-magnetic fraction, but this is of no technological use (Rodrigues et al., 2017; Zhu et al., 2019). This behavior can be explained by the fact that Ni occurs in two types of minerals – limonite and smectite (Xiao et al., 2020; Marzoughi and Pickles, 2024). The former concentrates in the magnetic fraction, while the latter concentrates in the non-magnetic one. Cobalt represents the only of the investigated metals that concentrates in non-magnetic fraction. At weak induction, it was detected in the magnetic fraction, while at medium induction all Co was already concentrated in the non-magnetic fraction (Wang et al., 2026).

The second part of the magnetic separation was performed on material with a particle size < 0.050 mm (Mweene et al., 2024). In addition to the coarse matrix, the material was also separated on the fine matrix (Fig. 5). After the experience from the first part of the separation, only high induction was selected. For Cr, more than two-fold enrichment in the magnetic fraction from the coarse matrix (0.6897 wt. %) than from the fine matrix (0.3205 wt. %) can be observed. Similar trend is exhibited by Zn (0.0656 wt. % and 0.0295 wt. %, respectively). On the other hand, Fe and Ni show significant enrichment in magnetic fraction on the fine matrix. Both elements reached the highest measured concentrations in this fraction, specifically, 22.0281 wt. % Fe and 1.0497 wt. % Ni compared to the input concentration of 6.4352 wt. % and 0.3960 wt. %, respectively. In the case of Mn, the measured concentrations in the magnetic fraction for fine and coarse matrix are very similar (0.4952 wt. % and 0.5150 wt. %, respectively). Cobalt, as in the first part of the magnetic separation, is concentrated in non-magnetic fraction for both matrices.

The last part of the magnetic separation focused exclusively on the behavior of Co and Ni, which showed different trends than the remaining metals. In contrast to the previous separations, the input material was pretreated. Addition of this technological step aimed at liberation of Ni from the smectite structure by its degradation. To degrade the smectite, heating to 130 °C for 12 hours, exposure to ozone for 10 minutes, and exposure to hard ultrasound at a frequency of 20 Hz for 5 minutes were used (Fig. 7). Both coarse and fine matrices were used for ozone and ultrasonic

pretreatment, while only fine matrix was employed for thermal degradation. Cobalt was detected in the heat-degraded sample in the non-magnetic fraction, where its concentration increased to 0.0164 wt. % compared to the input (0.0108 wt. %). Better results were observed for ozone and ultrasonic pretreatment, where concentrations of 0.0274 wt. % and 0.0251 wt. % Co, respectively, were measured in the non-magnetic fractions. Concentrations only slightly elevated compared to the input raw material were measured in the magnetic fraction on the fine matrix (0.0126 wt. % and 0.0147 wt. %, respectively). No Co was detected in the magnetic fraction on the coarse matrix. For Ni, similar to Co, it showed that thermal degradation does not result in significant enrichment. The input, magnetic and non-magnetic fractions have similar Ni concentrations of about 0.4 wt. %. Better results are observed for the material treated by ozone, where Ni concentrated in magnetic fraction on the fine matrix (0.5389 wt. %) and very slightly on the coarse matrix (0.4401 wt. %) compared to the input (0.4023 wt. %). The ultrasound-treated sample exhibits the same trend: higher Ni concentration in the magnetic fraction was measured on fine matrix (0.6277 wt. %) and slightly lower on the coarse matrix (0.4294 wt. %) compared to the ozone pretreatment.

It turns out that to obtain a concentrate of selected metals, it is better to use a high magnetic induction than a low one. For some elements, such as Fe or Ni, the use of a fine matrix, or a combination of coarse and fine matrices within a single separation, appears to be advantageous. All metals, except Co and Ni, are significantly concentrated in the fine matrix. By contrast, cobalt is concentrated exclusively in the non-magnetic fraction when separated on the coarse matrix. Part of Co is torn down into the magnetic fraction on the fine matrix. For Ni, it turned out to be advantageous to perform smectite degradation on the input material. After degradation, Ni concentrates primarily in the magnetic fraction (more on the fine matrix than on the coarse one), yet it occurs in a relatively high concentration (similar to the input) in the non-magnetic fraction.

CONCLUSION

The results of technological pretreatment and tests show that the particle size plays a fundamental role in the initial concentration of the metals of interest. Unfortunately, no universal technology based on magnetic separation which would lead to the enrichment of all metals at once has been found. Nickel in particular is very difficult to concentrate in both the non-magnetic and magnetic fractions due to its occurrence in two different types of minerals. Conversely, cobalt was successfully concentrated in the non-magnetic fraction, both with and without pretreatment. For further research, it would be interesting to perform magnetic separation of the fine fraction below 0.1 mm in suspension on a magnet which allows a higher magnetic induction than 1.2 T. Especially in the case of Ni, much higher

concentrations than presented in this work could be achieved. Even so, the magnetic separation results show the possibility of pretreatment of the finest fraction of laterite ore depleted of Ni, Co and other metals. It has been shown that it is possible to insert economically and environmentally friendly technological pretreatments before the actual metallurgical processes, which can help to concentrate the elements of interest and thus reduce the resulting volume of metallurgically processed ore. At the same time, they are in line with the strategy of processing the entire volume of the raw material, as they are intended to use all the fractions generated by these pretreatments.

The current processing of laterite ore lacks effective pretreatment of the material. There are also no studies available that address ore pretreatment. This study reveals the possibility of using some specific technological steps prior to the actual metallurgy, such as particle sorting and magnetic separation.

DECLARATIONS

ACKNOWLEDGMENTS

The authors would like to thank the other researchers of the Czech Geological Survey and the Czech University of Life Sciences Prague for their help in this study.

AUTHOR'S CONTRIBUTIONS

Material collection, technological pretreatment, and analysis: Štrba, M., Ptíčen, F., Pachťová, M.
Written the first draft of the manuscript: Štrba, M.
Commented on previous versions of the manuscript: Wittlingerová, Z., Poňavič, M.
Communication, revision, and editing of the review: Wittlingerová, Z., Poňavič, M.
All authors contributed to the conception and design of this study. All authors read and approved the final manuscript.

AVAILABILITY OF DATA AND MATERIALS

The data and materials presented in this article are available upon request.

FINANCIAL SUPPORT AND SPONSORSHIP

Authors are grateful to the Project No. SS02030023 „Rock Environment and Natural Resource RENS“ of the Technological Agency of the Czech Republic for funding.

CONFLICT OF INTEREST

All authors declared that there are no conflicts of interest.

ETHICAL APPROVAL AND CONSENT TO PARTICIPATE

Not Applicable.

CONSENT FOR PUBLICATION

Not Applicable.

REFERENCES

- Beneš, H., Donato, R.K., Ecorchard, P., Popelková, D., Pavlová, E., Schelonka, D., Pop-Georgievski, O., Schrekker, H.S. and Štengl, V.: 2016, Direct delamination of graphite ore into defect-free graphene using a biphasic solvent system under pressurized ultrasound. *RSC Adv.*, 6, 6008–6015. DOI: 10.1039/C5RA23654A
- Bruker AXS: 2015, *Diffraction.Eva*, 4.1. Karlsruhe, Germany.
- Butt, C.R.M. and Elias, M.: 2003, Nickel Laterites: A Review. *SEG Newsl.*, 54, 1–18. DOI: 10.5382/SEGnews.2003-54.fea
- Chang, Y., Zhao, K. and Pesic, B.: 2016, Selective leaching of nickel from prereduced limonitic laterite under moderate HPAL conditions-Part I: Dissolution. *J. Min. Metall., Sect. B Metall.*, 52, 2, 127–134. DOI: 10.2298/JMMB151102023C
- Daler, M., Horák, R. and Mátl, V.: 1970, Hydrosilicate Ni-ores in Czechoslovakia. Alternative recalculation, MS Final report, Unigeo Ostrava, MS Czechoslovak Geological Survey, Prague, (in Czech).
- Dehaine, Q., Tijsseling, L., Glass, H. and Törmänen, T.: 2021, Geometallurgy of cobalt ores: A review. *Miner. Eng.*, 160. DOI: 10.1016/j.mineng.2020.106656
- Elias, M.: 2002, Nickel laterite deposits-geological overview, resources and exploitation. Giant ore deposits: Characteristics, genesis and exploration. CODES Centre of Ore Deposit Research. Spec. Publ., 4, 205–220.
- European Commission: 2023, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol, M., Veeh, C., Study on the critical raw materials for the EU 2023 – Final report, Publications Office of the European Union. DOI: 10.2873/725585
- Gabriel, Z.: 1988, Quartzite materials of the weathering mantle of the Křemže ultrabasic rock complex. Dissertation, MS Czechoslovak Geological Survey, Prague, (in Czech).
- Gates-Rector, S. and Blanton, T.: 2019, The powder diffraction file: a quality materials characterization database. *Powder Diffr.*, 34, 4, 1–9. DOI: 10.1017/S0885715619000812
- Gultom, T. and Sianipar, A.: 2020, High pressure acid leaching: a newly introduced technology in Indonesia. IOP Conference Series: Earth and Environmental Science, 413. DOI: 10.1088/1755-1315/413/1/012015
- Institute of Materials Science, University of Connecticut. Available from: <https://www.ims.uconn.edu/rigaku-zxs-primus-iv-xrf-spectrometer/>. [Last access on 6 January 2026]
- Kaya, Ş. and Topkaya, Y.: 2011, High pressure acid leaching of a refractory lateritic nickel ore. *Miner. Eng.*, 24, 1188–1197. DOI: 10.1016/j.mineng.2011.05.004
- Komnitsas, K., Petrakis, E., Bartzas, G. and Karmali, V.: 2019, Column leaching of low-grade saprolitic laterites and valorization of leaching residues. *Sci. Total Environ.*, 665. DOI: 10.1016/j.scitotenv.2019.01.381
- Lottermoser, B.G.: 2011, Recycling reuse and rehabilitation of mine wastes. *Elements*, 7, 6, 405–410. DOI: 10.2113/gselements.7.6.405
- Marzoughi, O. and Pickles, C.A.: 2024, Solid state reduction and magnetic separation of nickeliferous laterite ores: Review and analysis. *J. Ind. Eng. Chem.*, 140, 65–87, DOI: 10.1016/j.jiec.2024.05.056

- Meshram, P., Abhilash, Dr. and Pandey, B.: 2019, Advanced review on extraction of nickel from primary and secondary sources. *Miner. Process. Extr. Metall. Rev.*, 40, 157–193. DOI: 10.1080/08827508.2018.1514300
- Ministry of the Environment: 2024, Raw material resources of the Czech Republic. *Mineral Resources 2024*, (in Czech). available at: <https://cgs.gov.cz/system/files/2025-05/surovinove-zdroje-ceske-republiky-2024.pdf>
- Mweene, L., Gomez-Flores, A., Jeong, H.E., Ilyas, S. and Kim, H.: 2024, Challenges and future in Ni Laterite Ore Enrichment: A Critical review. *Miner. Process. Extr. Metall. Rev.*, 45, 6, 539–563. DOI: 10.1080/08827508.2023.2214668
- Oxley, A. and Barcza, N.: 2013, Hydro-pyro integration in the processing of nickel laterites. *Miner. Eng.*, 54, 2–13. DOI: 10.1016/j.mineng.2013.02.012
- Oxley, A., Smith, M.E. and Caceres, O.: 2016, Why heap leach nickel laterites? *Miner. Eng.*, 88, 53–60. DOI: 10.1016/j.mineng.2015.09.018
- Ptíčen, F. and Zítko, V.: 2018, Method of obtaining concentrates of rare and strategic elements, oxides and minerals by selective magnetic separation. Patent No. 306697, (in Czech).
- Pulzová, A., Švagr, V., Tojšil, K., Urban, K., Vacek, J. and Zámek, J.: 1958, Final report with reserves calculation of the Křemže deposit. Ni - ores. Status as of 1 January 1958. West Bohemia Ore Exploration, Prague. MS Czechoslovak Geological Survey, Prague, (in Czech).
- Rodrigues, F., Pickles, C.A., Peacey, J., Elliott, R. and Forster, J.: 2017, Factors affecting the upgrading of a nickeliferous limonitic laterite ore by reduction roasting, thermal growth and magnetic separation. *Minerals*, 7, 9, 176. DOI: 10.3390/min7090176
- STAL technology: 2026. Available from: https://www.staltechnology.com/stal_technology. [Last accessed on 6 January 2026]
- Stanković, S., Stopić, S., Sokić, M., Marković, B. and Friedrich, B.: 2020, Review of the past, present, and future of the hydrometallurgical production of nickel and cobalt from lateritic ores. *Metall. Mater. Eng.*, 26, 199–208. DOI: 10.30544/513
- Stanković, S., Kamberović, Ž., Friedrich, B., Stopić, S.R., Sokić, M., Marković, B. and Schippers, A.: 2022, Options for hydrometallurgical treatment of Ni-Co lateritic ores for sustainable supply of nickel and cobalt for European battery industry from South-Eastern Europe and Turkey. *Metals*, 12. DOI: 10.3390/met12050807
- Tyurnina, A.V., Tzanakis, I., Morton, J., Mi, J., Porfyrakis, K., Maciejewska, B.M., Grobert, N. and Eskin, D.G.: 2020, Ultrasonic exfoliation of graphene in water: A key parameter study. *Carbon*, 168, 737–747. DOI: 10.1016/j.carbon.2020.06.029
- Wang, S., Fu, Y., He, D. and Wang, T.: 2026, Comprehensive review of mineral processing and metallurgical technologies for cobalt ores. *Miner. Eng.*, 236, 2. DOI: 10.1016/j.mineng.2025.109947
- Watling, H.R., Elliot, A.D., Fletcher, H.M., Robinson, D.J. and Sully, D.M.: 2011 Ore mineralogy of nickel laterites: controls on processing characteristics under simulated heap-leach conditions. *Aust. J. Earth Sci.*, 58, 7, 725–744. DOI: 10.1080/08120099.2011.602986
- Xiao, J., Ding, W., Peng, Y., Chen, T., Zou, K. and Wang, Z.: 2020, Extraction of nickel from garnierite laterite ore using roasting and magnetic separation with calcium chloride and iron concentrate. *Minerals*, 10, 4, 352. DOI: 10.3390/min10040352
- Zhu, D., Pan, L., Guo, Z., Pan, J. and Zhang, F.: 2019, Utilization of limonitic nickel laterite to produce ferronickel concentrate by the selective reduction-magnetic separation process. *Adv. Powder Technol.*, 30, 2, 451–460. DOI: 10.1016/j.appt.2018.11.024