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Main geological and mineralogical characteristics of the Cajálbana lateritic deposit, Pinar del Río, Cuba

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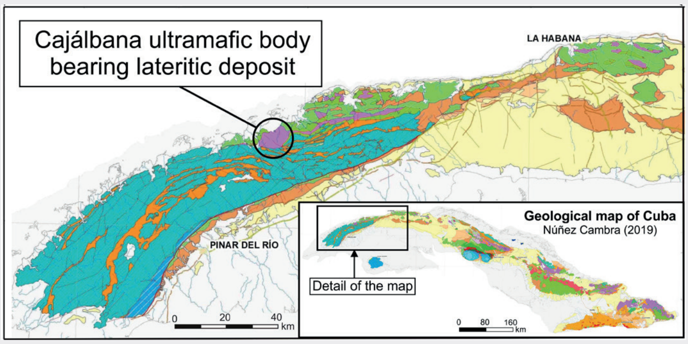
Abstract: This paper submits the main geological and mineralogical characteristics of the Cajálbana lateritic deposit located in Pinar del Río, Cuba, a perspective deposit for the Cuban nickel industry. Presented study took into account altogether 470 samples from 80 vertical boreholes. The contents of principal elements and compounds of Fe, Ni, Co, Mn, SiO_2, Al_2O_3, MgO and Cr_2O_3 were determined by the Inductively Coupled Plasma (ICP) method. The results of geological field research, combined with mineralogical and geophysical previous investigations, have revealed that the serpentinized pyroxene peridotites with increased iron, nickel and chrome contents represent the primary source of Ni and Fe mineralization in laterites of the Cajálbana deposit.

Key words: lateritic deposit, peridotite, serpentinite, Cajálbana

Graphical abstract



Highlights

- Paper informs about regional geology, ancient exploration and new research methodology applied in the Cajálbana lateritic deposit including processing and evaluation of mineralogical and geochemical data.
- Positive results obtained improve nickel reserves in Cuba and may contribute to beneficial mining in the Cajálbana locality.

Introduction

Lateritic deposits worldwide are of importance, as they are the source of 59 % of primary nickel (Nickel Institute, 2017). In Cuba, lateritic deposits, associated with nickel and iron-bearing weathering crusts, occur in several regions. They have been studied for more than sixty years from geological and technological points of view due to their importance for the Cuban nickel industry, producing one of the main goods of the Cuban economy (Ruiz Quintana, 2016). Because the deposits currently exploited in the eastern part of the country will be gradually exhausted, it is essential to assure their replacement by new ones to sustain nickel production. This is the reason of increased research of the deposits in the western regions of Cuba such as the Cajálbana lateritic deposit in the Pinar del Río province.

History of exploration in cajálbana area

First exploration for nickel in the Cajálbana serpentinite massif was committed by the American company *Cuban Iron* in 1939–1943. This exploration covered the western part of the area with lateritic weathering crust present *in situ*, as well as its redeposited occurrences, located north of the province of Pinar del Río (Commercial Caribbean Nickel, 2009) in the Sierra del Rosario of La Palma municipality (GeoCuba, 2002; Figs. 1–3).

The works of the Soviet geologist Ogarkov (e.g. Ogarkov, 1970) stand out by the *limonite* ore resources calculation in this Cuban mineral deposit, using earlier data of the *Cuban Iron* Company.

Other investigations in this area are related to exploration of ferruginous minerals for the use in metallurgical industry (Yujvit et al., 1966), or as an iron corrector at cement production (Gómez, 1988). Research was limited to study the upper part of the vertical lateritic profile with high iron content (zone of the unstructured ochre with pellets – iron concretions – OICP) and redeposited laterites to the area at the edges of the Cajálbana serpentine massif. This research did not contribute new knowledge of their ores.

Following geological research in the Cajálbana massif and its surroundings aimed to evaluate the nickel and iron potential (Carmona, 1995), as well as precious metals (Martín et al., 1998). This investigation improved existing geological data, by applying fieldwork and interpretation of geophysical and relief maps.

The *Geominera Oriente* Company developed the most recent works in the period 2008–2009 (Cardoso Velázquez et al., 2018), retrieved by *Commercial Caribbean Nickel* (project in 2009; see reference), constituting the basis of our investigation.

Other researchers have managed to generalize the geological information related to the formation of chromite deposits, associated with ophiolites, as well as their quantitative evaluation, modeling and estimation of possible new deposits (Díaz et al., 1987).

Concerning the volume of reserves, it is generally considered that the most important genetic type for Cuba is that having the lateritic-saprolitical vertical profile (Ariosa Iznaga et al., 2003). Cajálbana mineral deposit belongs into this group also.

For the studies of Cajálbana mineral deposit, the geophysical methods such as magnetic susceptibility have been also used for estimating the weathering crust mineral quality (Hernández Ramsay, 2018).

Therefore, the fundamental objective of this work is to present main geological and mineralogical characteristics of the Cajálbana lateritic mineral deposit for possible metallurgical use, taking advantage of the technologies recently used by the Cuban nickel industry (Ruiz Quintana, 2016; Figs.1–4).

The working hypothesis of this research states that, depending on the physical, chemical and mineralogical characteristics of the Cajálbana mineral deposit, the decision on its possible industrial use can be made.

Geological setting of the Cajálbana deposit

The western part of Cuba is framed by the Guaniguanico Terrain with Cangre metamorphic belt, both representing the Mesozoic basement, as well as by the zone of **Mesozoic ophiolitic assemblage**, encompassing also the remnants of the **Cretaceous volcanic arc** (Fig. 2). Part of ophiolites is the **Cajálbana ultramafic body**, which perspective Ni/Fe mineralization was investigated and the results are presented in this study. Due to the Paleocene-Eocene convergence of oceanic crust on Mesozoic basement

Fig. 1. Exploration in the Cajálbana laterite deposit. 1 – Drilling facility UGB-50 with drilling capacity up to 100 m with spiral drilling and 65 mm of diameter, 2–3 – Cajálbana area is typical with red lateritic soil and contains traces after exploration works, 4 – complementary drilling for *limonitic* ore applying the Atlas Copco portable drill.

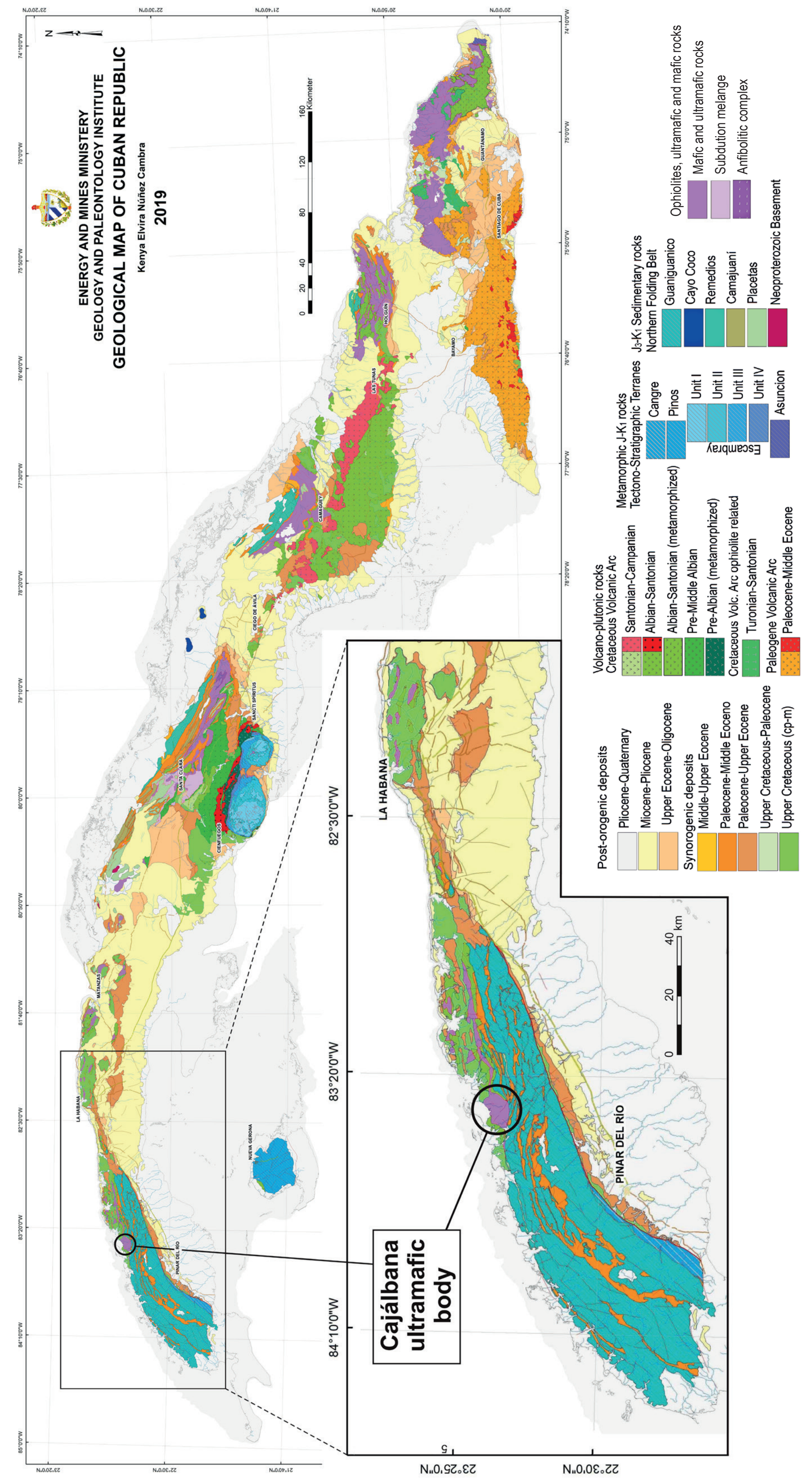


Fig. 2. Geological map of Cuba (taken after Núñez Cambra, 2019).

(Pardo, 2009; Núñez Cambra, 2019), the Paleogene sequences are folded and faulted and the post-obduction cover is represented by Late Eocene-Quaternary sediments. The ultramafic ophiolitic sequences after exhumation and obduction underwent lateritic weathering and became a source of economic Ni mineralization, contributing to Cuban raw material potential.

The **Cajálbana ophiolites** of the northern belt of Cuba crop out in a series of elongated bodies between localities of Baracoa to the east and Cajálbana to the west. The deformed tabular bodies of ophiolites, sometimes thick up to 6 km, were during their placement intermixed with tectonic slices of Cretaceous volcanic arc. Currently, the Cajálbana ophiolites lie in a tectonic position on sequences of the Sierra de Guaniguanico and are covered with tectonic slices of volcanites of the Bahía Honda Formation. This situation is best observable south of the Guaniguanico area in the Sierra del Rosario (Commercial Caribbean Nickel, 2009).

The Cajálbana deposit represents part of the ferronickeliferous crusts of the Cajálbana ultrabasic massif, which is located in the province of Pinar del Río, 13 and 38 km from the towns of La Palma to the West and Bahía Honda to the East respectively and 70 km from the city of Pinar del Río to the SW – the provincial capital (Oficina Nacional de Recursos Minerales, 2018).

Tectonites of peridotites

In the Cajálbana massif, the peridotite complex has a depleted lherzolite character and distinct foliation produced by convergent processes. The lineation predominantly trends to the north and is well observable in the field. Under the microscope, a strong preferred orientation of the olivine was revealed, which indicates an intense high-temperature ductile deformation. The deformation inventory includes also pull-apart microstructures, undulose extinction in olivine, lamellae solution of clinopyroxenes in orthopyroxenes, kink band boundaries, etc. According to Fonseca (1989) the peridotites and their serpentinite equivalents exhibit a primitive and relatively uniform composition of their main metals.

In the Cajálbana area all contacts of peridotites with underlying and surrounding geological units are tectonic – the boundary is represented either by their thrust plane or vertical faults. The area is penetrated with two main fault systems trending generally NE-SW and NW-SE (Fig. 4). They influence the courses of some rivers, which is verified through geological criteria such as the alignment of the river beds and is visible also in the digital model of the relief. Subordinate to and associated with main faults, a system of lower-order faults was observed. The local cracks in the outcrop scale are filled with calcium and

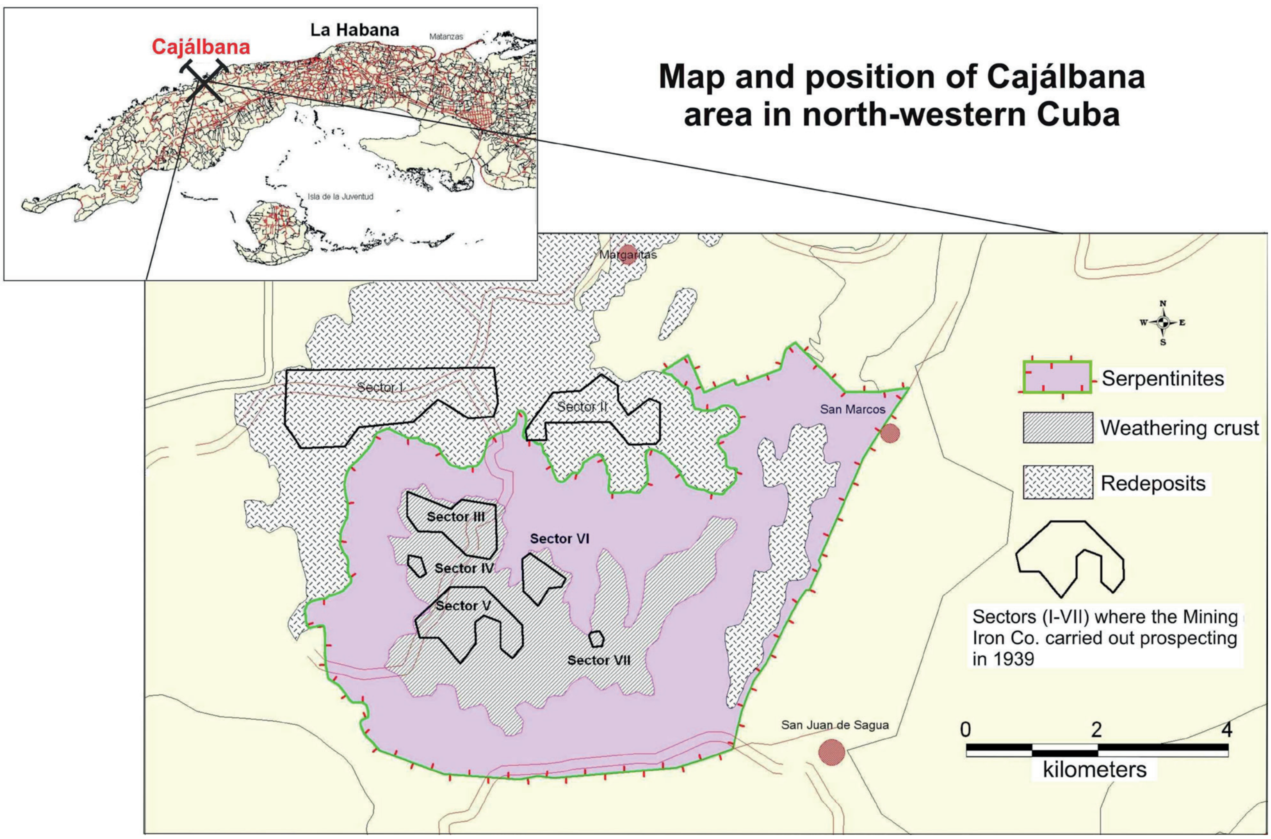


Fig. 3. Geographical location of Cajálbana (Oficina Nacional de Recursos Minerales, 2018).

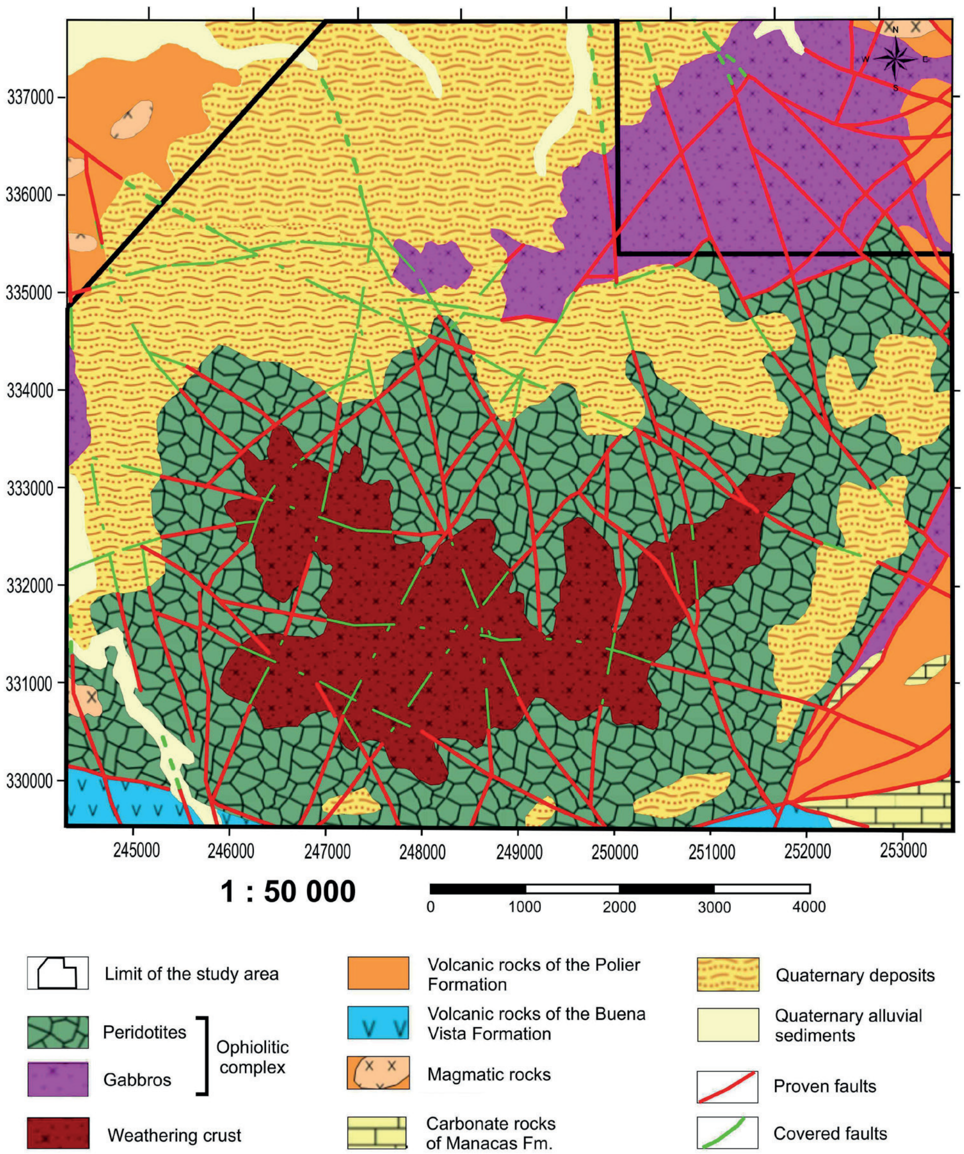


Fig. 4. Geological-tectonic map of the Cajálbana research area, prepared from the original map of Maximov et al. (1978). The Ophiolitic complex, Polier Fm., Buena Vista Fm., are from Cretaceous and Manacas Fm., from the lower Eocene (fore deep).

magnesium carbonate mineralization that we relate to the origin of the faults.

Tectonics represents one of the factors conditioning the formation of mineral deposits. Especially in the case of lateritic deposits the brittle faults play an important role, facilitating the circulation of surface water through the host rocks and enabling leaching and transport of soluble elements and by this way directly influencing also the geometry of the deposits and the distribution of ore types.

The recent version of the geological-tectonic map of the Cajálbana deposit research area (Fig. 4) was prepared from the geological map at a scale of 1 : 50 000 (Maximov et al., 1978), in which assumed faults were verified, digitized and reported. Likewise, Digital Relief Model (DEM) was constructed, as well as the different vector layers for faults, rivers and streams, have contributed in our research to decipher the brittle discontinuities – the pathways for the water penetration that facilitates the weathering.

Materials and methods of mineralogical study

For achieving the research objectives the combination of methods of chemical, and mineralogical analyses was applied.

Sampling

A sampling network was based on expert criteria for representative sampling in the studied Cajálbana lateritic mineral deposit, based on Geological Exploration Project (Commercial Caribbean Nickel, 2009). Technological and mineralogical samples were taken with the Hollow Auger

Integral drilling method applying 89 mm diameter spiral augers, providing granulometric fractions, which were selected for the study from individual lithological horizons (Fig. 5). The sampling within the same lithology was also done, as variations in the physical and mineralogical characteristics had been observed macroscopically during the field geological research (lithological profiles, accompanying mineralization and fundamental colour change).

Analytical techniques used

Chemical analyses were performed using mainly the Inductively Coupled Plasma (ICP) method for determinations of the main element. The oxides were calculated using a stoichiometry conversion factor for Al_2O_3, SiO_2, MgO, Cr_2O_3, MnO, Fe_2O_3, NiO, CoO, FeO, FeO-Cr. The losses by ignition (LOI– Loss on ignition, in Spanish PPI) were determined by gravimetric method using a muffle furnace with the temperature range from 350 ºC to 850 ºC.

Mineralogical analyses were carried out by X-ray diffractometer – model Panalytical X'PERT3, under the following working conditions: Gonio-type scan in [° 2θ] angular register from 4.0042 to 79.9962 with step distance in ° 2θ of 0.0080 with Cu radiation and nickel filter. Difference of potential equal to 40 kV, current of 30 mA and calibration of the equipment with external silicon standard. Finally the mineralogical and chemical recalculations were performed per sample.

Results and discussion

Lithological characteristics of the ore in the Cajálbana lateritic mineral deposit

The presence of vertical lithological profiles of the lateritic-saprolitical type was verified. According to the terminology defined by Lavaut Copa (2003), there is a predominance of the Structurally Incomplete Saprolitical Laterite that from the surface of the cut to its base has chemical characteristics shown in Fig. 6.

Tab. 1

Average contents of the main chemical elements in lithology of the Cajálbana lateritic mineral deposit.

Vertical lithological profiles	Chemical elements (%)					
	Ni	Fe	Co	Si	Mg	Al
OICP	0.96	41.0	0.072	3.6	1.1	7.9
OI	1.14	43.1	0.057	2.9	1.0	6.5
OEF	1.07	36.2	0.136	7.2	2.6	5.8
OEI	1.26	20.7	0.041	16.1	9.0	3.4
RML	1.17	8.6	0.018	20.0	16.5	1.6

Note: For an explanation of abbreviations in the left column see Fig. 6.

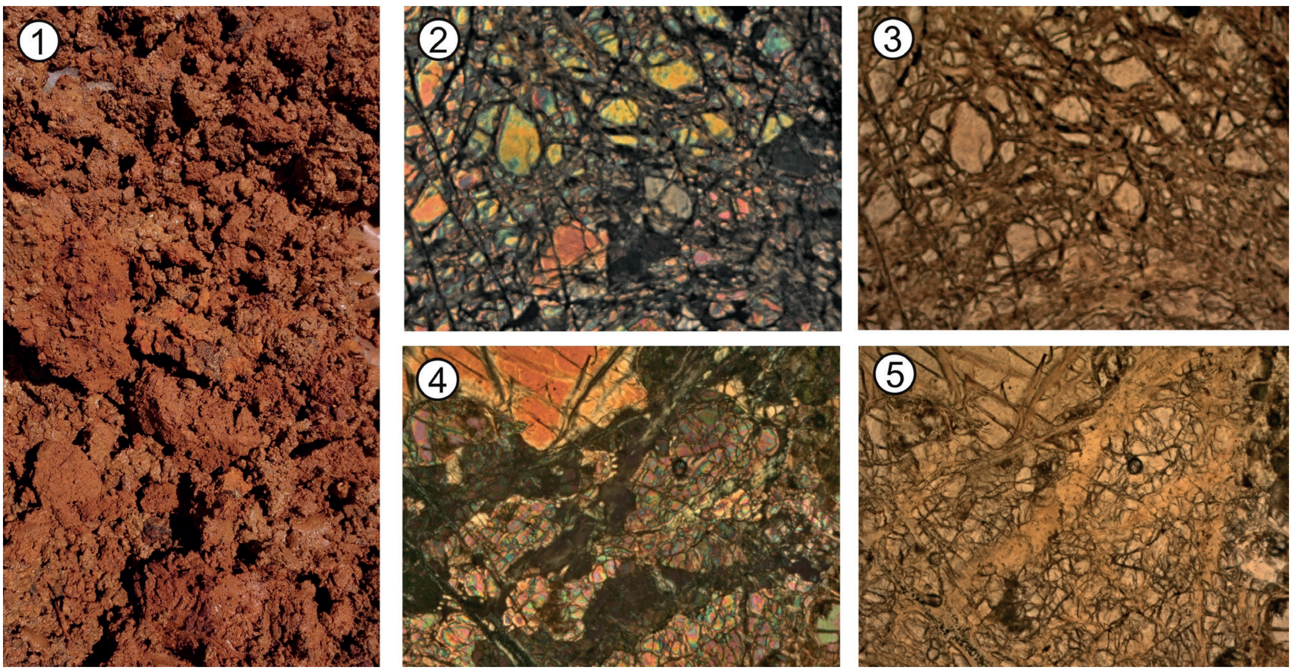
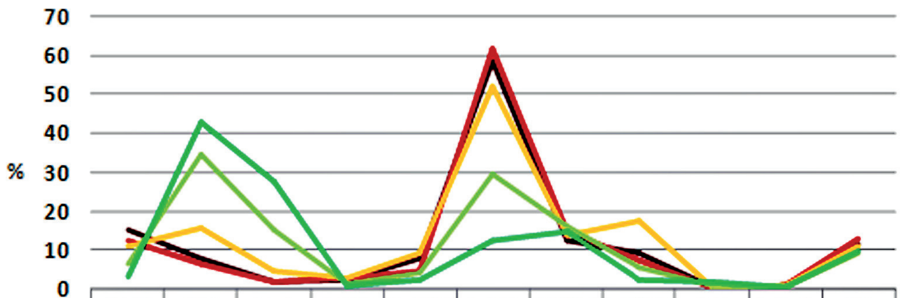


Fig. 5. Typical *limonite*-bearing weathering crust (1; width of view 20 cm) and photomicrograph of harzburgite from Cajálbana area (2–3; crossed and parallel nicols; x10) with dominating olivine (rounded) and clinopyroxene as well as small proportion of plagioclase. Serpentinized harzburgites (4–5; crossed and parallel nicols; x25) have newly formed chrysotile minerals. Photomicrographs 2–5 were done by the AXIO-LAB.A1 polarized light microscope with camera AXIOCAM ERs 5s.

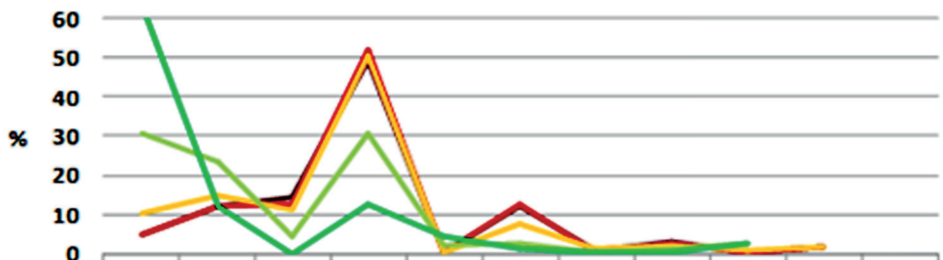
The behaviour of the average contents of the main chemical elements in vertical lithological profiles shows a depthward increase in the content of nickel, silica and magnesium; while the trend of iron, cobalt and aluminum contents is generally the opposite. Table 1 presents a characteristic composition of elements in lateritic profile, the contents are considered to be perspective for the Cuban nickel industry.

It was corroborated that the study area is characterized by the dominating presence of ultramafic rocks (harzburgites and related serpentinites, lherzolites, websterites and more sparsely dunites). They are usually green, with shades ranging from light to dark, of massive structure, constituted by bastitized orthopyroxenes, olivine (relict or serpentinized) and minerals of the serpentine group, as shown in Fig. 7.



	Al2O3	SIO2	MgO	Cr2O3	MnO*10	Fe2O3	NIO*10	CoO*100	FeO	FeO_Cr	PPI
OICP	14.9	7.7	1.7	2.3	7.6	58.6	12.2	9.2	0.2	0.8	11.2
OI	12.3	6.2	1.7	2.6	4.6	61.5	14.5	7.2	0.1	0.8	12.6
OEF	11.0	15.4	4.3	2.4	9.1	51.7	13.6	17.4	0.1	0.9	11.1
OEI	6.5	34.4	15.0	1.4	4.0	29.6	16.0	5.2	0.7	0.5	9.0
RML	2.9	42.7	27.4	0.7	2.4	12.2	14.8	2.3	1.8	0.2	9.5

Fig. 6. Average content of oxides in lithological profiles in the Cajálbana lateritic mineral deposit. Used symbology: OICP – Unstructured ochre with iron concretions; OI – Unstructured ochre without iron concretions; OEF – Final structural ochre; OEI – Initial structural ochre; RML – Leaped and disintegrated serpentinites. Ordering OICP → OI → OEF → OEI → RML is from the top of lithological profile depthward.



	MinSerp	MinArc	Gibbs	Goeth	Magnet	EspCrom	MinMang	Hemat	Cuarzo	Maghem	Pirox
OICP	4.9	12.1	14.4	49.3	0.5	12.3	0.9	3.2	0.5	1.8	
OI	4.9	12.3	12.4	52.1	0.4	12.6	0.5	2.5	0.4	1.8	
OEF	10.1	14.7	11.1	50.6	0.4	7.7	1.1	2.1	0.9	1.6	
OEI	30.5	23.2	4.6	30.8	2.1	2.5	0.5	1.2	2.6		2.4
RML	63.6	12.0	0.0	12.5	4.6	1.1	0.3	0.2	2.6		2.8

Fig. 7. Average mineralogical composition by lithological profiles in the Cajálbana lateritic mineral deposit. MinSerp – serpentine, MinArc – clay, Gibbs – gibbsite, Goeth – goethite, Magnet – magnetite, EspCrom – chromiferous spinel, MinMag – magnesite, Hemat – hematite, Cuarzo – quartz, Mghem – maghemites, Pirox – pyroxenes. For further symbology see Fig. 6.

Characteristics of ores

The most abundant ore consists of *limonite* and in vertical lithological profiles it is mainly located from the OICP to the OEF, whose recalculation results are shown in Fig. 8.

Mineralogically, the ores of this deposit are characterized by the dominant presence of goethite, serpentine and clay minerals as shown in Fig. 9:

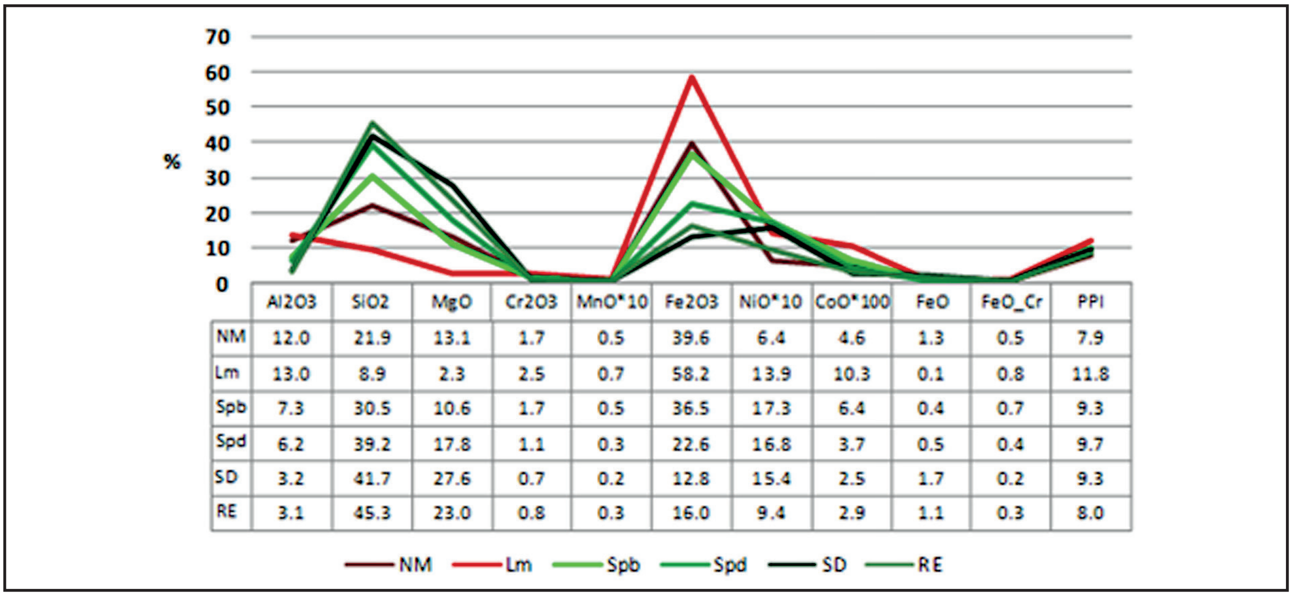
Main results of the Cajálbana deposit characterization

The overall mineralization coefficient of the study area is 70.74 %, consisting mainly of structurally incomplete lateritic profiles developed in ultramafic protolith (peridotites) and very subordinate mafic rocks (ca. 11 %).

The mineralization present in the explored area is derived mainly from the pyroxenic peridotite rocks. Tectonically, the study area is dissected with the main fault systems trending NE-SW and NW-SE. They are interpreted as crucial for the surface water circulation.

A Database was created with the results of 470 samples analysed by ICP, taking into account the interpretation of the results of aero-geophysical flights from the 1980s (Díaz, Padilla & Corbea, 1987) in order to estimate the deposit thickness for modelling with the geological-mining software Micromine®, being the result the total tonnage of ore with the Ni cut off greater than or equal to 0.7 % determined is 51 million tons in the inferred category. The results by type of ore shown in Table 2.

As can be seen in Table 2, the ***limonite* ore (Lm)** has high mineralization values (48.99 %), with relatively high Fe, MgO, Al_2O_3 and Cr_2O_3 contents and an average value very similar to that of the Moa deposits in Cuba. Limonite prevailed in the Cajálbana area, representing 48.99 % of the total tonnage and this is very important for the Cuban nickel industry in the acid leaching processing plant as it is more suitable for this type of hydrometallurgical process.



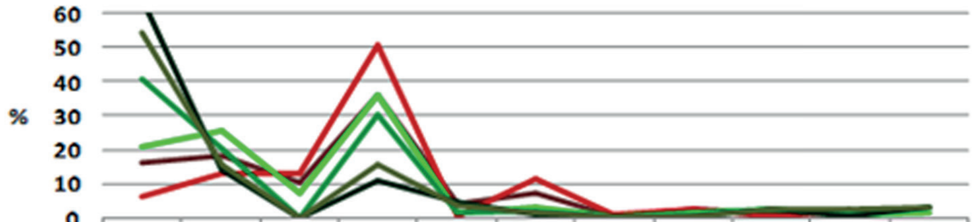
	Al2O3	SiO2	MgO	Cr2O3	MnO*10	Fe2O3	NiO*10	CoO*100	FeO	FeO_Cr	PPI
NM	12.0	21.9	13.1	1.7	0.5	39.6	6.4	4.6	1.3	0.5	7.9
Lm	13.0	8.9	2.3	2.5	0.7	58.2	13.9	10.3	0.1	0.8	11.8
Spb	7.3	30.5	10.6	1.7	0.5	36.5	17.3	6.4	0.4	0.7	9.3
Spd	6.2	39.2	17.8	1.1	0.3	22.6	16.8	3.7	0.5	0.4	9.7
SD	3.2	41.7	27.6	0.7	0.2	12.8	15.4	2.5	1.7	0.2	9.3
RE	3.1	45.3	23.0	0.8	0.3	16.0	9.4	2.9	1.1	0.3	8.0

Fig. 8. Average content of oxides per ore in the Cajálbana lateritic mineral deposit. Used symbology: NM – ferricrete with nickel content below 0.7 %, Lm – *limonite*, Spb – soft saprolite, Spd – hard saprolite, SD – hard serpentine, RE – sterile rock.

Tab. 2
Average content of the main chemical elements by type of ore in the Cajálbana lateritic mineral deposit.

Ore	Chemical contents (%)								
	Fe	Ni	Co	MgO	Al_2O_3	MnO	Cr_2O_3	Pm.i (m)	Cm (%)
Lm	41.41	1.03	0.081	2.59	12.84	0.60	2.57	2.73	48.99
Spb	27.41	1.11	0.058	10.65	9.16	0.54	1.79	2.58	7.80
Spd	16.62	1.07	0.033	21.10	4.57	0.34	1.03	5.76	10.32
Sd	10.07	1.24	0.021	27.94	2.52	0.21	0.65		2.10
Average contents in whole deposit	40.10	1.05	0.060	17.70	8.90	0.50	1.85	5.26	

Explanations: Lm – *limonite*, Spb – soft saprolite, Spd – hard saprolite, Sd – hard serpentinite, Pm.i – Industrial average potential (thickness in meters), Cm – Coefficient of mineralization (%).



	MinSerp	MinArc	Gibbs	Goeth	Magnet	EspCrom	MinMang	Hemat	Cuarzo	Maghem	Pirox
NM	16.3	18.4	10.6	36.1	4.1	7.0	0.6	2.6	1.3	1.2	
Lm	6.0	12.9	13.0	50.5	0.4	11.5	0.8	2.6	0.5	1.7	
Spb	20.7	25.3	7.1	36.0	1.4	3.1	0.5	1.5	2.7	1.1	1.7
Spd	40.8	20.2	0.0	30.4	1.4	2.2	0.3	0.9	2.3	0.7	2.9
SD	64.3	13.8	0.0	11.1	4.7	1.1	0.3	0.3	2.5	0.4	2.8
RE	54.6	15.7	0.0	15.7	3.3	1.2	0.3	0.6	2.7	2.5	3.0

NM   Lm   Spb   Spd   SD   RE

Fig. 9. Average mineralogical composition of ore in the Cajálbana lateritic mineral deposit: For symbology see Fig. 6 and 7.

On the other hand, **soft saprolite (Spb)** reaches an average mineralization coefficient of 7.80 %, with an extremely unstable character, which exhibits a very limited diffusion due to the existence of non-mineralized boreholes with average Fe, Ni and Co contents corresponding to the characteristics of the deposits of Punta Gorda, Moa, in the northeast part of the country.

Hard saprolite (Spd) has mineralization coefficient of 10.32 %, with extremely unstable character and limited diffusion, although somewhat higher than that of soft saprolite (Spb). The **hard serpentine (SD)** has a limited development, characterized by mineralization coefficient of 2.1 % and is extremely dispersed or unstable.

In general, it can be considered that the minerals from the Cajálbana lateritic mineral deposit in the municipality of La Palma, Pinar del Río province, have average contents of the main chemical elements that are currently being studied by the Cuban nickel industry, similar as those from lateritic nickel and iron deposits of the eastern region of Cuba, with an average ore potential of 5.26 m and mineralization of 17.3 %, which is proved by revealed main physical and chemical characteristics of this prospective deposit for the Cuban nickel industry.

From the mineralogical point of view, the Cajálbana deposit consists mainly of Fe and Ni bearing minerals, specifically the goethite, followed by serpentine and clay minerals and in smaller extent the chromiferous spinels and pyroxenes. In addition, the predominance of iron, nickel and chromium ores in these peridotites is typical.

Conclusions

The ore from the Cajálbana lateritic mineral deposit in the municipality of La Palma, Pinar del Río province, is characterized by chemical elements and compounds with contents similar to those in the eastern region of Cuba where these minerals are processed by the Cuban nickel industry, having the average iron content of 40.10 %, nickel 1.05 % and cobalt 0.06 %, representing beneficial elements.

The lateritic mineral deposit is characterized mineralogically by the presence of Fe and Ni bearing minerals, mainly goethite and serpentine minerals, which resemble nickel and iron deposits in the eastern region of Cuba.

Recent knowledge of geological and mineralogical characteristics of the Cajálbana lateritic deposit confirms its similarity to the rest of the Cuban lateritic minerals deposits, with great potential for industrial processing, applying existing technologies.

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Hlavné geologické a mineralogické charakteristiky lateritického ložiska Cajálbana v provincii Pinar del Río, Kuba

Príspevok charakterizuje geologickú stavbu zóny mezozoickej obdukovanej ofiolitovej sekvencie vystupujúcej paralelne s osou Kuby v jej severnej zóne (obr. 2) s dôrazom na nové perspektívne Fe-Ni ložisko Cajálbana pri obci La Palma v provincii Pinar del Río v západnej časti Kuby (obr. 1, 3 a 4). Toto ložisko vzniklo intenzívnym lateritickým zvetrávaním povrchovej časti obdukovaných serpentinizovaných peridotitov (obr. 1, 4 a 5), ktoré spolu s výskytmi hornín kriedového vulkanického oblúka sa v súčasnosti nachádzajú na mezozoickom fundamente Guaniguanico. Ložisko je prestúpené početnými zlomami smeru SV – JZ a SZ – JV, ktoré sú dôležité pri cirkulácii povrchovej vody a prispeli k intenzívnemu lateritickému zvetrávaniu.

Chemická analýza reprezentatívnych vzoriek z jednotlivých horizontov kôry zvetrávania (tab. 1) a tiež rudy z ložiska Cajálbana (obr. 6 a 8) pri celkovom počte 470 vzoriek z 80 vertikálnych vrtov preukázali porovnateľný obsah prvkov a zlúčením, ako sa už skôr zistil na ložiskách vo východnej časti Kuby, ktoré sa ťažia v súčasnosti – priemerný obsah Fe dosahuje 40,10 %, Ni 1,05 % a Co 0,06 % (tab. 2). Podobne aj mineralogický výskum doložil prítomnosť Fe a Ni minerálov, predovšetkým goethitu a serpentínových minerálov (obr. 7 a 9), korešpondujúcich s minerálmi na Ni a Fe ložiskách ťažených v súčasnosti.

Terénnym geologickým prieskumom opierajúcim sa o mineralogický a skorší geofyzikálny výskum sa potvrdilo, že primárnym zdrojom zvýšeného obsahu Fe, Ni a Co na ložisku Cajálbana sú serpentinizované peridotity a budúca ťažba ich lateriticky zvetraných častí bude ekonomickým prínosom pre krajinu.

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