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REVIEW ARTICLE

Geological and economic criteria about the existence of scandium in the lateritic deposits of Moa, Cuba

Criterios geológicos y económicos sobre la existencia de escandio en los yacimientos lateríticos de Moa, Cuba

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Abstract

ICP-MS analyses have revealed the existence of scandium in the lateritic nickel and cobalt ores of the Moa region (Cuba). This article reviews the available information about this element and geological and economic criteria are offered about the contents of scandium in the ores of Camarioca East, Yagrumaje North and Yagrumaje South lateritic deposits and in the tailings of the metallurgical plants of the region. The distribution of scandium mineralization in the lateritic profile predominates in the limonitic horizon, where goethite, gibbsite and hematite appear. The reported values of the average contents of scandium show economic potential for developing geological exploration projects that consider the extraction of metal as a byproduct of nickel and cobalt production in Moa, using acid leaching technology under pressure.

Keywords: scandium; lateritic ore; nickel and cobalt deposits; Moa.

Resumen

Análisis de ICP-MS han revelado la existencia de escandio en las menas lateríticas de níquel y cobalto de la región de Moa (Cuba). En el presente artículo se revisa la información disponible sobre este elemento y se ofrecen criterios geológicos y económicos sobre los contenidos de escandio en las menas de los yacimientos lateríticos Camarioca Este, Yagrumaje Norte y Yagrumaje Sur y en las colas de las plantas metalúrgicas de la región. La distribución de la mineralización de escandio en el perfil laterítico predomina en el horizonte limonítico, donde aparecen goethita, gibbsita y hematita. Los valores de los contenidos medios de escandio reportados evidencian potencialidad económica para el desarrollo de proyectos de exploración geológica que consideren la extracción del metal como subproducto de la producción de níquel y cobalto en la región de Moa, utilizando la tecnología de lixiviación ácida a presión.

Palabras clave: escandio; menas lateríticas; depósitos de níquel y cobalto; Moa.

1. INTRODUCTION

The scandium (Sc), together with yttrium (Y) and lanthanides, represent a group of 17 metals known as rare earth elements (REE), that show similarities in physical and chemical properties and in the geochemical behavior; they don´t appear as native metals in the Earth's crust and are concentrated in halides, carbonates, oxides, phosphates and silicates.

There are about 200 mineral species that contain rare earths, but the most important ore formers are the bastnäsita [(Ce,La)(CO_3)F] and monazite [(Ce, La,Nd,Th) PO_4], containing each about 70 % weight of rare earth oxides (British Geological Survey, 2010). Xenotime (YPO_4) is added to these minerals, which generally contains, besides yttrium, considerable amounts of heavy rare earths elements (HREE): Y, Tb, Dy, Ho, Er, Tm, Yb, and Eu-Lu), being the main source of these metals (Voncken, 2016).

On the other hand, scandium is widely dispersed in the lithosphere in the form of solid solutions in more than 100 mineral species and associated with ferromagnesian minerals, such as hornblende, biotite and pyroxenes. The basalts and gabbro have concentrations between 5 - 48 ppm of scandium oxide (Sc_2O_3) equivalent (Klein, 2003). The scandium enrichment occurs also in other minerals such as beryl, cassiterite, columbite, garnet, muscovite, rare earth minerals and wolframite (U.S. Geological Survey, 2013).

Scandium can be obtained from thortveitite [$Sc_2Si_2O_7$], which contains between 44 - 48 % of Sc_2O_3, bazzite [$Be_3(Sc,Fe^{3+},Mg)_2Si_6O_{18}.Na_{0.32}.nH_2O$)], euxenite (Y,Ca,Ce,U,Th)(Nb,Ta,Ti)$_2$O$_6$] and gadolinite [$Y_2Fe^{2+}Be_2O_2(SiO_4)_2$], rare earth minerals, and is commonly obtained as a by-product of uranium and tantalum refining process (Hoatson, Jaireth and Miezitis, 2011).

According to U.S. Geological Survey (2018), identified resources of scandium are reported in Australia, Canada, China, Kazakhstan, Madagascar, Norway, Philippines, Russia, Ukraine and the United States of America. Due to its low concentration, scandium is produced almost exclusively as a by-product of the processing of various minerals or previously recovered from industrial tailings and waste. In China, it is obtained as a by-product of the production of titanium and rare earths, in Russia from apatite and in Kazakhstan and Ukraine from uranium. The main uses of scandium are related to aluminum-scandium alloys and manufacture of solid oxide fuel cells (SOFCs). Other important uses are reported in ceramics, electronics, lasers, lighting and radioactive isotopes.

The aluminum-scandium alloys, containing between 0.1 % and 0.5 % of scandium, are destined for the aerospace industry, manufacture of sports equipment and other high performance applications. In the SOFCs, scandium is added to an electrolyte based on zircon for improving energy efficiency, reducing the reaction temperature and lengthening the useful life of the cell. SOFCs are expected to play the main role in developing batteries for the transport industry based on electricity, so in recent years it has been awakened a global interest for scandium (Hoatson, Jaireth and Miezitis, 2011).

The growing demand for the main scandium compounds and the own metal for special applications in the high-tech industry in key sectors and areas of the international economy, is reflected in the prices of its commercialization (Table 1), for which it is identified as a strategic metal.

Table 1. Variation of the Price of metallic scandium and its compounds marketable in the period 2013-2017 (USD)

Compounds (USD/gram):	**2013**	**2014**	**2015**	**2016**	**2017**
Acetate: 99,9 % purity	51,90	43,00	43,00	44,00	44,00
Chloride: 99,9 % purity	148,00	123,00	123,00	126,00	124,00
Fluoride: 99,9 % purity	253,00	263,00	263,00	270,00	277,00
Iodide: 99,999 % purity	228,00	187,00	187,00	149,00	183,00
Oxide: 99,99 % purity	5,00	5,00	5,10	4,60	4,60
Metal (USD/gram):					
Distilled dendritic	213,00	221,00	221,00	228,00	226,00
Ingot of scandium	175,00	134,00	134,00	107,00	132,00
Sc-Al alloy, USD/Kg	155,00	386,00	220,00	340,00	350,00

Source: U.S. Geological Survey (2018): *Mineral Commodity Summaries* 2018.

Lateritic deposits of nickel and cobalt present a distribution very wide geographic range (Figure 1). According to U.S. Geological Survey (2018) Australia, Brazil, Cuba, Philippines and Indonesia accumulate about 62 % of global nickel reserves. The largest volume of cobalt reserve is concentrated in the Congo Kinshasa (49.3 %), Australia (16.9 %), Cuba (7.0 %) and Philippines (3.9 %).

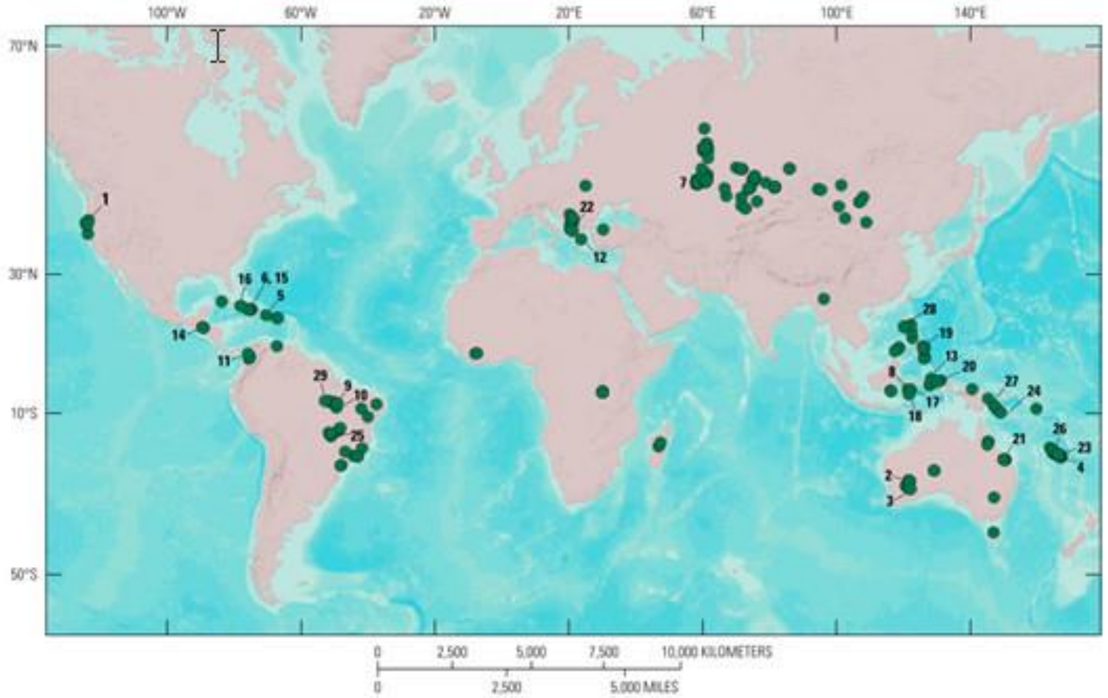

Figure 1. Global distribution of nickel (Ni) and nickel-cobalt (Ni-Co) lateritic deposits. Source: *Geological Survey of Canada* (Eckstrand et al. 2008) and *U.S. Geological Survey Open-File Report* 2011–1058 (Berger et al. 2011).

1.1. Geochemical behavior of scandium mineralization in laterites associated with mafic and ultramafic rocks

The significant content of scandium in mafic rocks is explained because this metal is incorporated in pyroxenes, amphiboles and more rarely in the olivine. Therefore, pyroxenites show higher contents of scandium than peridotites. In the chemical weathering process scandium has a motionless behavior, so other elements are enriched in the lateritic profile when leaching it, replacing the Fe^{3+}, Al^{3+} and Ti^{3+}, where it tends to exist in Fe oxides, Fe oxyhydroxides, Ti oxide, Al hydroxides and in the minerals of the group of serpentine (Maulana, Sanematsu and Sakakibara, 2016).

In the model of scandium mineralization deposit in laterites associated with mafic and ultramafic rocks (Hoatson, Jaireth and Miezitis, 2011) they point out that, in contrast to the group of lanthanide and yttrium, which show a genetic and spatial relationship with alkaline igneous felsic rocks, scandium has a close affinity with mafic and ultramafic igneous rocks with high magnesium content. As a result of prolonged weathering process of these rocks, under favorable microclimate conditions, tectonics, relief and other factors, some elements such as magnesium and silica are removed and others are retained such as iron, nickel, cobalt and scandium (Proenza, 2015).

According to Chassé and other researchers (2016), the scandium mineralization in the Syerston-Flemington deposit, developed on a complex of mafic-ultramafic rocks of the Alaska-Ural type, occurs due to the high concentration of this metal in clinopyroxenes. The weathering process favors enrichment of circulating water flows in the regolith, below the water table; the seasonal precipitation of the goethite allows the Sc^{3+} adsorption and during dry periods the hematite, which develops from goethite, can incorporate part of the Sc adsorbed in its crystalline structure.

However, this process is limited by the difference in size between the coordination links of Sc^{3+} and Fe^{3+}, although such differences do not influence the goethite adsorption capacity under conditions of almost neutral pH; during the laterite weathering of ultramafic and mafic rocks, the scandium behaves like a heavy element of the REE. The Sc enrichment factor between the bedrock and the fresh saprolite is close to 5 and in relative to the limonitic horizon that factor can reach up to 10 times. In the limonitic horizon, the goethite is 80 % of scandium, while hematite carries the remaining 20 % (Chassé et al., 2016).

Proenza (2015), quoting Audet (2009) and Aiglsperger (2015), describes that there is a high correlation between the contents of Sc and those of Fe_2O_3; in lateritic deposits and due to the scandium contents, the deposits of the Caribbean are comparable with deposits from Australia. Scandium could be recovered as a by-product during the operations of extracting Ni-Co, because it is easily leached with sulfuric acid in the high-pressure acid leaching process (HPAL).

Some researchers (Aiglsperger *et al*. 2013, 2016), when describing the geochemical behavior of scandium in nickel and cobalt lateritic profiles in Cuba, refer to the fact that mineralizing Sc is concentrated in zones rich in secondary oxides of Fe and Mn. The contents of scandium in saprolite vary between 8 - 17 ppm, while in limonitic horizon, where goethite predominates (> 50 % by weight) and, in a lower proportion, maghemite, hematite and gibbsite, increase up to 70 - 98 ppm, observing a high correlation between Sc and the Fe_2O_3 (Figure 2).

The nickel, cobalt and scandium concentration in the lateritic profile mainly owes to a limited and selective geochemical migration, both in vertical sense as horizontal; in the case of nickel, it migrates in form of Ni^{2+} in aqueous solution from the limonitic horizon to the saprolitical horizon, replacing Mg^{2+} in the minerals of serpentine group, where reaches the highest concentration.

The differentiated geochemical behavior of nickel, cobalt and scandium originates enrichment areas in the lateritic profile of these metals, whose spatial distribution shows certain regularity (Figure 3).

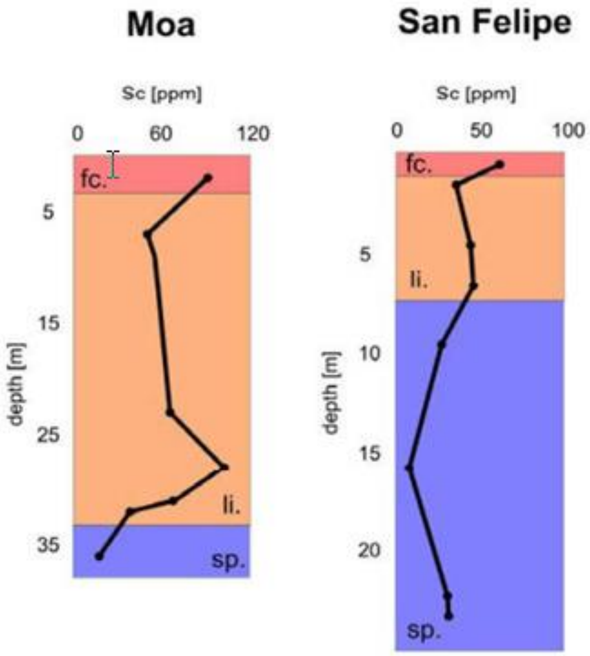

Figure 2. Distribution of scandium contents in Cuba lateritic profiles. Source: Aiglsperger et al (2013). sp. = saprolite; li = limonite; fc. = ferricrete.

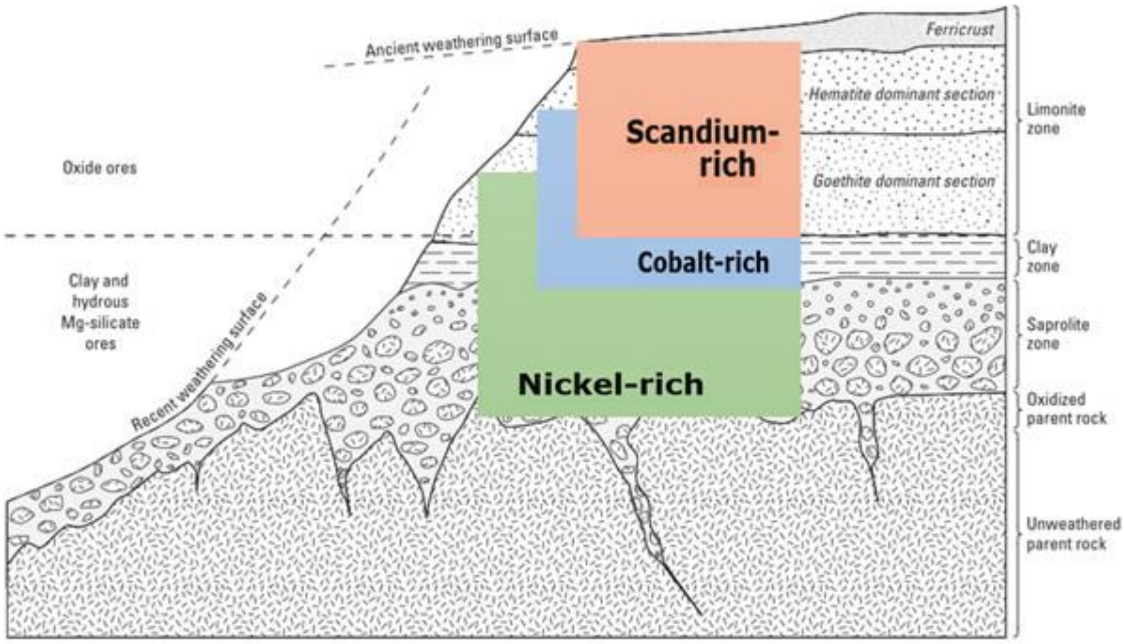

Figure 3. Enrichment zones of nickel, cobalt and scandium in an idealized cross section through a nickel lateritic weathered profile saprophytic-lateritic. (*U.S. Geological Survey Scientific Investigations Report* 2010–5070–H, 38). Modified by the authors.

1.2. Geological features of lateritic deposits on mafic and ultramafic rocks in the region of Moa, Cuba

The bedrock of nickel and cobalt laterite deposits from mineral district of Moa are composed mainly by peridotites, predominating the harzburgite and dunite, with greater or lesser degree of serpentinization. In these rocks, constituted by ferromagnesian minerals, are reported nickel and cobalt contents between 0.2 % - 0.4 % and 0.01 % - 0.02 % respectively, values that increase due to the meteorization process of serpentinized peridotites and serpentinites.

According to the classification in the descriptive-genetic models of the Metallogenic Map of the Republic of Cuba, scale 1: 250 000, (Torres-Zafra, Lavaut-Copa and Cazañas-Díaz, 2017), there are three types of weathering profiles: lateritic, lateritic-saprolitical (the most widespread) and lateritic-saprolitical - clayey. The limonitic horizon of the lateritic profile is mainly composed by goethite (65 % -77 %), which controls between 73 % and 96 % of the nickel content. In the lateritic-saprolitical deposits, the saprolitical zone is mainly formed by minerals from serpentines group (22 % - 65 %) that together with nickeliferous smectite (12 % -35 %) contain between 82 % and 85 % of nickel. In lateritic-saprolitical argillaceous deposits the smectites (nontronite and montmorillonite) provide the greatest amount of nickel (14 % - 44 %). In all cases, between 80 %

and 90 % of cobalt, is mostly associated with manganese ores, mainly asbolane (wad rich in Co-Mn) and subordinately lithiophorite. Other metals associated are iron (Fe), magnesium (Mg), chromium (Cr) and aluminum (Al).

In Cuban lateritic Ni and Co deposits the presence of vanadium (V), gold (Au), platinum group elements (PGE), rare earths (REE) are also reported and, more recently, the existence of scandium, mainly associated with the limonitic horizon, which includes ferricrust (Proenza, 2015; Cazañas-Diaz *et al.,* 2016; Ministry of Energy and Mines- IGP, 2015; Aiglsperger *et al*., 2016)

In the western sector of the mineral district of Moa, lateritic deposits predominate (example: Moa Oriental, Camarioca Norte and Yagrumaje Oeste), whereas lateritic-saprolitical deposits are more frequent in the eastern sector (examples: Punta Gorda, Yagrumaje Norte, Yagrumaje Sur and Camarioca Este), as shown in Figure 4.

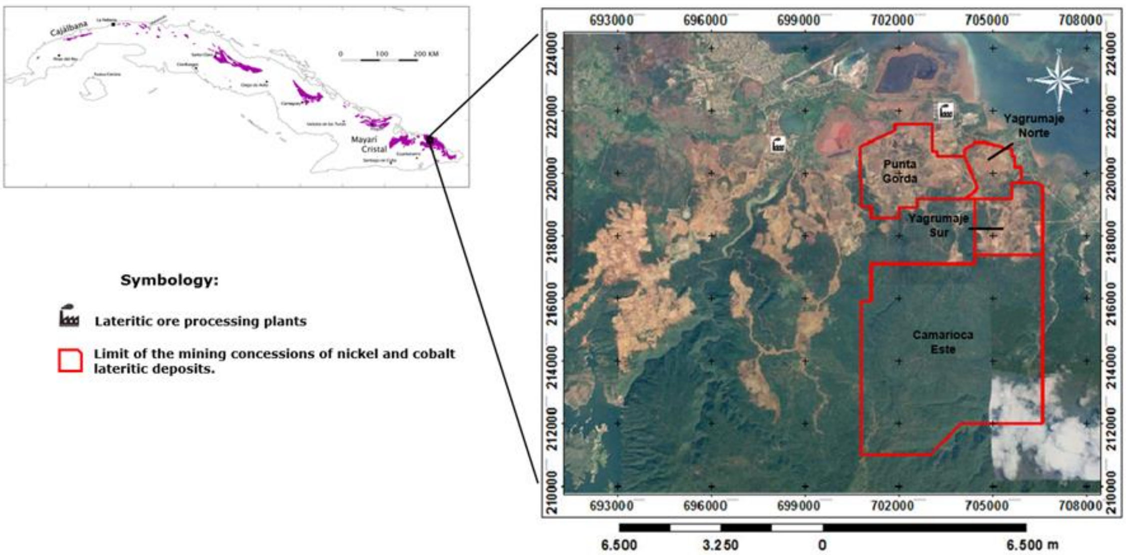

Figure 4. Geographic location of Punta Gorda lateritic deposits, Yagrumaje Norte, Yagrumaje Sur and Camarioca Este located in the Eastern sector of the Mineral District of Moa, represente don a satellite image of the region.

1.3. Posibilities of obtaining scandium from lateritic nickel and cobalt ores

In recent years, several scientific publication refer to research technical reports and feasibility studies made in different countries, which show the economic viability of obtaining scandium, as a by-product, by processing lateritic nickel and cobalt ores using high pressure acid leaching (HPAL).

Currently, the most significant projects that consider extracting Sc by HPAL technology are concentrated in Australia and the Philippines, where the following stand out (U.S. Geological Survey, 2018):

- Scandium International Mining's Nyngan Project (NSW, Australia) reports estimated reserves of 1.44 Mt, representing 590 t of Sc in situ, applying a cut-off of 155 ppm Sc. This project foresees to produce 38.5 t per year as of 2019.
- Clean TeQ's Syerston Project (NSW, Australia) is located in feasibility study phase and 45.7 million metric tons of measured and indicated resources, with 19 200 t of Sc_2O_3 in situ, applying a cut-off of 300 ppm for Sc.
- Scandium-Cobalt-Nickel (SCONI) Project (Queensland, Australia) is in the feasibility study phase, with resources measured and indicated estimated at 12 Mt, with 3 000 t of Sc2O3 in situ, applying a cut-off of 162 ppm Sc.
- Taganito HPAL Nickel Corporation (Philippines) that expects to produce 7.5 t/year of Sc2O3, from 2018.

In Moa, a high-pressure acid leaching plant (HPAL) is operating and it has been processing nickel and cobalt lateritic ores from the lateritic deposits of the western sector of this mineral district since the early 60's showing high rates of metallurgical efficiency.

This scenario suggests the need to clarify the economical and geological meaning of mineralization of Sc, whose existence has been recently established in Cuba, and can be an argument for developing geological prospecting projects and programs that allow to characterize the scandium mineralization features in each lateritic deposit and its possible industrial use as a by-product of the cobalt and nickel production, based on the substantial resources of laterites on mafic and ultramafic rocks in several regions of Cuba and a metallurgical plant in operations that uses HPAL technology.

2. METODOLOGY

Published data about scandium contents reported for the lateritic Ni and Co deposits were reviewed: Camarioca Este, Yagrumaje Norte and Yagrumaje Sur, whose ores are processed by Ernesto Che Guevara nickel plant, which uses ammoniacal - carbonate technology. The scandium contents reported in the tailings of this plant and in the feed ores to Moa Nickel S.A.-PSA metallurgical plant were also reviewed in order to reinterpret them.

The values reported for scandium were determined by using the method of ICP-MS.

3. RESULTS

The average content values of scandium in the deposits that currently are in exploitation in the mineral district of Moa show an increasing trend from the west to the east. The deposits of the western sector are represented by the ores fed to the Moa Nickel S.A.PSA plant and those of the eastern sector, by the ores of the Camarioca Este, Yagrumaje Sur and Yagrumaje Norte deposits, which are processed by the Ernesto Che Guevara nickel plant, which employs the carbonate-ammonia technology (see Figure 5). This statement is reinforced by the significant value of the scandium content reported in the tails of this plant.

The ores that feed the processing plant Moa Nickel S.A. PSA, have been characterized with specific determinations of the content of scandium, which confirm the existence of this metal in the deposits that are currently exploited in the western sector of the mineral district of Moa.

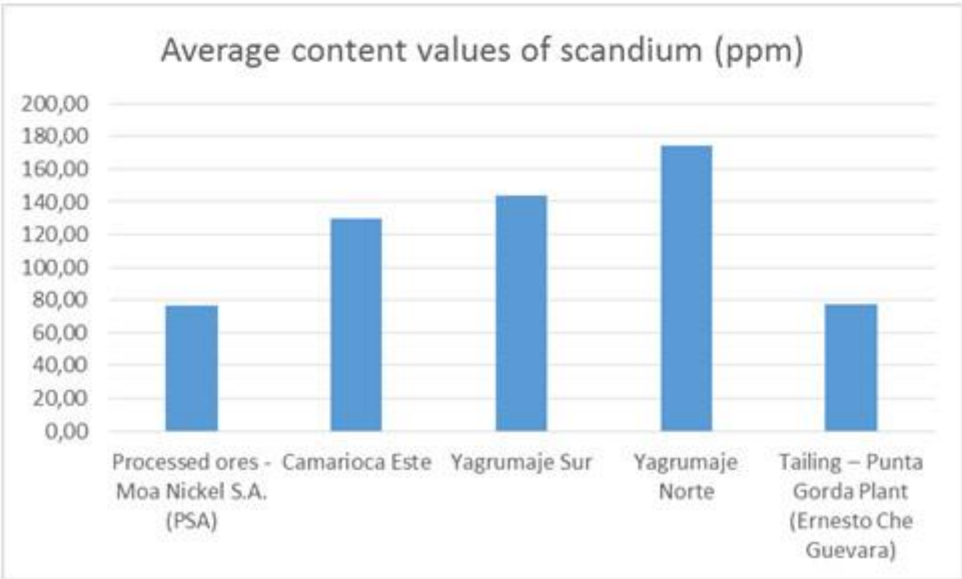

Figure 5. Values content of scandium (ppm) reported in the lateritic nickel and cobalt ores from Moa mineral district and in the tailing of Ernesto Che Guevara nickel plant. Source: Data from the Ministry of Energy and Mines (2015) and the Institute of Geology and Paleontology-Geological Survey of Cuba (2016). Modified by the authors.

4. DISCUSSION

The average contents of scandium in the ores fed to the Moa Nickel S.A. plant reach values close to 80 ppm. These ores come from the limonitic profile of nickel and cobalt lateritic deposits in the western part of the Moa mineral district. However, the technological process leaches these metals, evidencing the potential of this processing plant to obtain scandium as a marketable by-product of nickel and cobalt production. The contents of scandium in situ could be higher, because the ores that are fed to the technological process are extracted from the low and intermediate levels of the limonitic horizon, where the contents of scandium do not reach their maximum values.

In the lateritic deposits of Ni and Co in the eastern sector of Moa, which are currently processed by the Ernesto Che Guevara nickel plant, mean values of Sc between 130 - 175 ppm are reported (Figure 4).

In the descriptive - genetic model of the lateritic - saprolitic type deposits, where Yagrumaje Norte, Yagrumaje Sur and the NE part of Camarioca Este are classified, it is described that within protolites besides dunites, harzburgites and serpentinites, pyroxene ultramafites appear (lherzolites, wehrlites and olivinic pyroxenites) and subordinated gabbroic rocks, such as troctolites, olivine gabbro, norite, and others (Torres-Zafra et al., 2017).

As it is known, pyroxene ultramafites and gabbroic rocks are carriers of Sc mineralization and these rocks are located more frequently towards the East and NE part of the Moa mineral district, where lateritic profiles of the limonitic-saprolitic type predominate.

5. CONCLUSIONS

- The existence of scandium in lateritic nickel and cobalt deposits of Moa mineral district allows confirming potentials for the development of geological prospecting projects for nickel-cobalt-scandium ores, considering the presence of extensive weathering crusts on mafic and ultramafic rocks of the ophiolite complex, covering favorable lithological varieties for this type of mineralization.
- The existence of the Moa Nickel S.A.-PSA processing plant, which processes Ni and Co lateritic ores by HPAL technology, with all the mining and industrial infrastructure available, constitute favorable factors to consider the possibility of necessary capital investments for a future extraction of scandium as by-product of nickel and cobalt production.

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