

Revisiting the Luanga PGE-Ni-Cu deposit: how do the massive sulfide ores fit in?

Cesar F. Ferreira Filho
cesarf@unb.br



Instituto de Geociências – UnB

Acknowledgements



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Fundação de Apoio à
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Conselho Nacional de Desenvolvimento
Científico e Tecnológico

Mining Industry



Exploration geologists, academics and graduate students

Exploration Review

- **1983 DOCEGEO** (exploration branch of CVRD; now VALE). Mafic-ultramafic rocks and chromitites of the Luanga Complex were identified during regional exploration in the Serra Leste region.
- **1985 DOCEGEO**. Projeto Cromo. Geological mapping, soil geochemical survey (400 m × 40 m grid) and ground magnetometric survey in the Luanga Complex. Four diamond bore holes were drilled to test the thickness and lateral continuity of outcropping chromitites. The drilling intersected anomalous concentrations of Pt and Pd, including 9 m at 2.57 ppm of Pt + Pd (drill core LUFD-04).
- **1997 JV DOCEGEO-Barrick Gold**. Stream sediment campaign over the Luanga Complex area that identified Au anomalies (up to 3 ppm).
- **2000 VALE**. Projeto Au Serra Leste. A new soil geochemical survey to test the Au anomalies indicated by Barrick Gold. The sampling grid, covering the southern portion of Luanga Complex, indicated a 1 km long trend of Pt and Pd anomalies. Due to this anomalous trend with up to 1,450 ppb of Pt + Pd, Vale S.A. carried out additional soil geochemical surveys in the northern and central portions of the Luanga Complex, indicating a continuous soil anomaly along the stratigraphy (~ 4 km-long).
- **2001-2007 VALE** performed 79,335 m of diamond drilling and ore characterization tests in PGE-mineralized layered intrusions of the Serra Leste region. The resource drilling program in the Luanga Complex reached 45,174 m of diamond drilling and indicate a PGE deposit with resources of 142 Mt at 1.24 g/t PGE + Au and 0.11% Ni, for a given cut-off grade of 0.5 g/t PGE + Au. These resources were evaluated for a shallow (i.e., approximately 250 meters deep) open pit.
- **2021-2022 Acquired by BPG Minerals (name changed to Bravo Mining Co in 2022)**. Aggressive drilling program (Phase 1 – 25,000 m of diamond drilling by 2022). Intersection of massive Ni-Cu sulfides in August 2022.

First paper published after the discovery of the Luanga PGE-Ni deposit.
 Based on results from the evaluation program carried out by VALE (2001-2007).

Contribuições à Geologia da Amazônia – volume 5, 2007



Ferreira Filho C.F. *et al.* / Mineralizações estratiformes de EGP-Ni associadas a complexos acamadados em Carajás

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Mineralizações estratiformes de EGP-Ni associadas a complexos acamadados em Carajás: os exemplos de Luanga e Serra da Onça

**Cesar Fonseca Ferreira Filho⁽¹⁾, Fernando Cançado⁽²⁾, Carolina Correa⁽²⁾,
 Edésio Maria Buenano Macambira⁽³⁾, Lincoln Siepierski⁽²⁾ e Tereza Cristina Junqueira-Brod⁽²⁾**

(1) Instituto de Geociências, Universidade de Brasília (UnB), Asa Norte, Brasília, DF, 70910-900, e-mail: cesarf@unb.br

(2) Companhia Vale do Rio Doce (CVRD), Rodovia BR 262, Km 296, Caixa Postal 09, Santa Luzia, MG, 30030-970

(3) Serviço Geológico do Brasil (CPRM), Av. Dr. Freitas 3645, Bairro do Marco, Belém, PA, 66095-110

Published papers focused on different aspects of the Luanga Complex and PGE-Ni mineralization.

Magmatic structure and geochemistry

Chromitites

Ni-PGE mineralization

The Canadian Mineralogist
Vol. 59, pp. 1453-1484 (2021)
DOI: 10.3749/canmin.2100018

2021

THE EFFECTS OF POST-CUMULUS ALTERATION ON THE DISTRIBUTION OF CHALCOPHILE ELEMENTS IN MAGMATIC SULFIDE DEPOSITS AND IMPLICATIONS FOR THE FORMATION OF LOW-S-HIGH-PGE ZONES: THE LUANGA DEPOSIT, CARAJÁS MINERAL PROVINCE, BRAZIL

EDUARDO MANSUR[§] AND SARAH-JANE BARNES
Sciences de la Terre, Université du Québec à Chicoutimi, Québec, G7H 2B1, Canada

CESAR F. FERREIRA FILHO
Instituto de Geociências, Universidade de Brasília, Brasília-DF 70910-900, Brazil



Magmatic structure and geochemistry of the Luanga Mafic-Ultramafic Complex: Further constraints for the PGE-mineralized magmatism in Carajás, Brazil

Eduardo Teixeira Mansur, Cesar Fonseca Ferreira Filho *

Instituto de Geociências, Universidade de Brasília, Brasília, DF 70910-900, Brazil

Ore Geology Reviews xxx (2017) xxx-xxxx

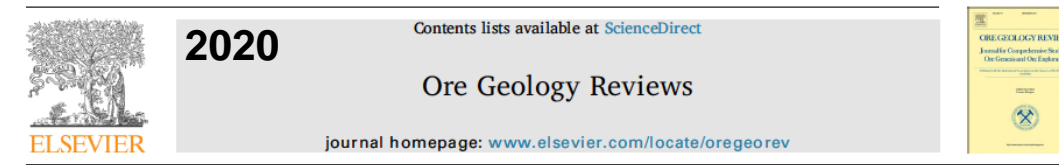


Chromitites from the Luanga Complex, Carajás, Brazil: Stratigraphic distribution and clues to processes leading to post-magmatic alteration

Eduardo Teixeira Mansur, Cesar Fonseca Ferreira Filho *

Instituto de Geociências, Universidade de Brasília, Brasília-DF 70910-900, Brazil

Ore Geology Reviews 118 (2020) 103340



The Luanga deposit, Carajás Mineral Province, Brazil: Different styles of PGE mineralization hosted in a medium-size layered intrusion

Eduardo T. Mansur^{a,1,*}, Cesar F. Ferreira Filho^a, Denisson P.L. Oliveira^b



Revisiting the Luanga PGE-Ni-Cu deposit: how do the massive sulfide ores fit in?

- Review the main features of the Luanga PGE-Ni-Cu deposit (previous collaboration research with VALE)
- Evaluate how new results impact previous understanding of the deposit (on-going collaboration research with BRAVO).

Luanga 2007 - VALE



Luanga 2022 - BRAVO

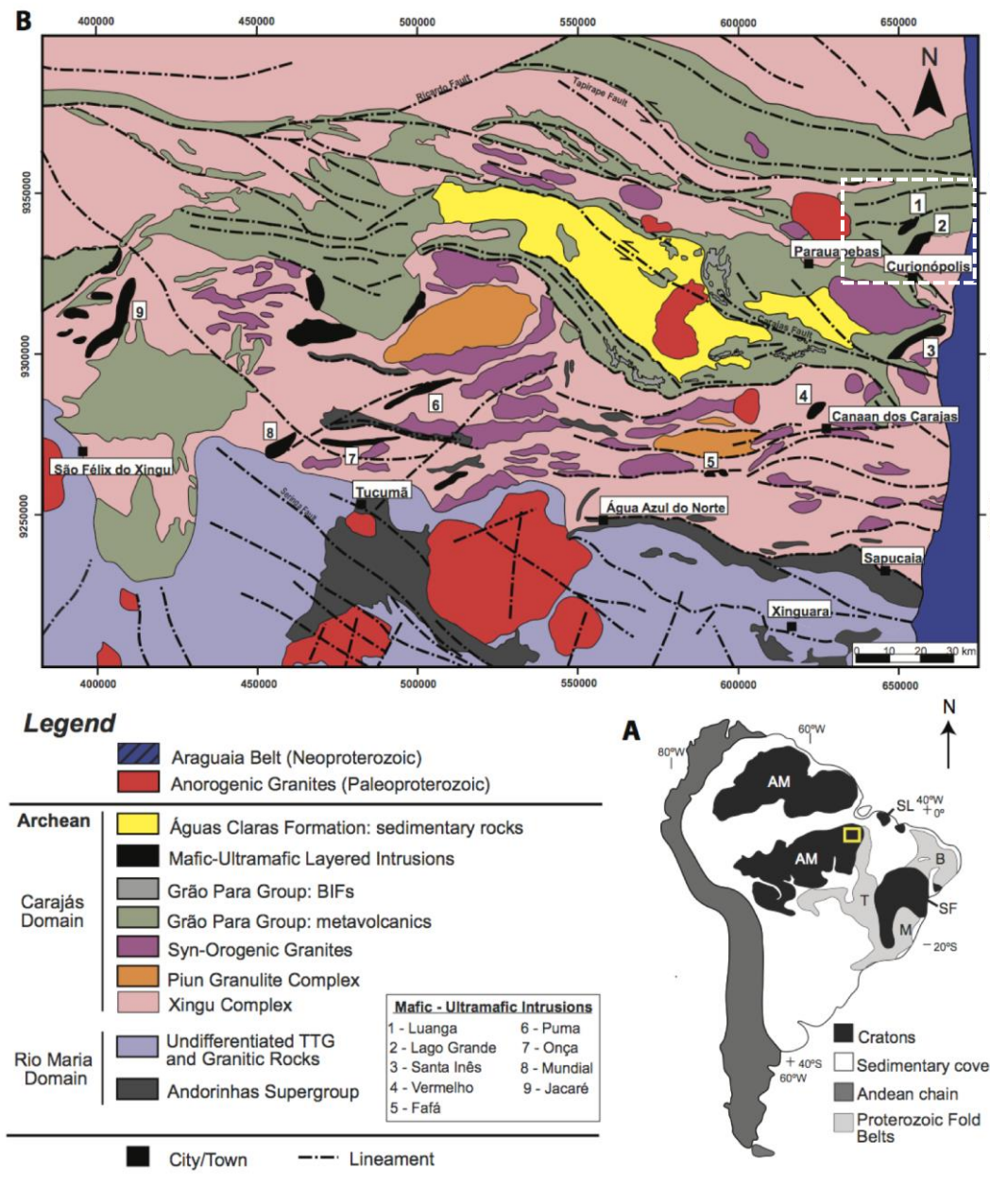


Carajás Mineral Province

I am deliberately skipping a presentation of the regional geology! Except for ...

Neoarchean Mafic-Ultramafic intrusions

- Abundant mafic-ultramafic intrusions occur in southern portion of the Carajás Domain (~ 250 km long).
- They include large layered intrusions characterized by thick piles of olivine cumulates that developed world-class Ni laterite deposits (e.g., Jacaré, Onça, Puma, Vermelho).
- Intrusions are located along major crustal scale faults.
- Similar ages (ca 2.76 Ga) of intrusions and bimodal volcanism indicate a coeval Neoarchean magmatic events (LIP).
- Intrusions of the Serra Leste Magmatic Suite returned abundant PGE anomalies or mineralized zones (Ferreira Filho et al. 2007).



Modified from Vasquez et al. (2008)

Serra Leste Magmatic Suite

A cluster of small- to medium-sized mafic-ultramafic intrusions.

These intrusions returned abundant PGE anomalies or mineralized zones during exploration for PGE deposits (Ferreira Filho et al. 2007; 2015).



2015

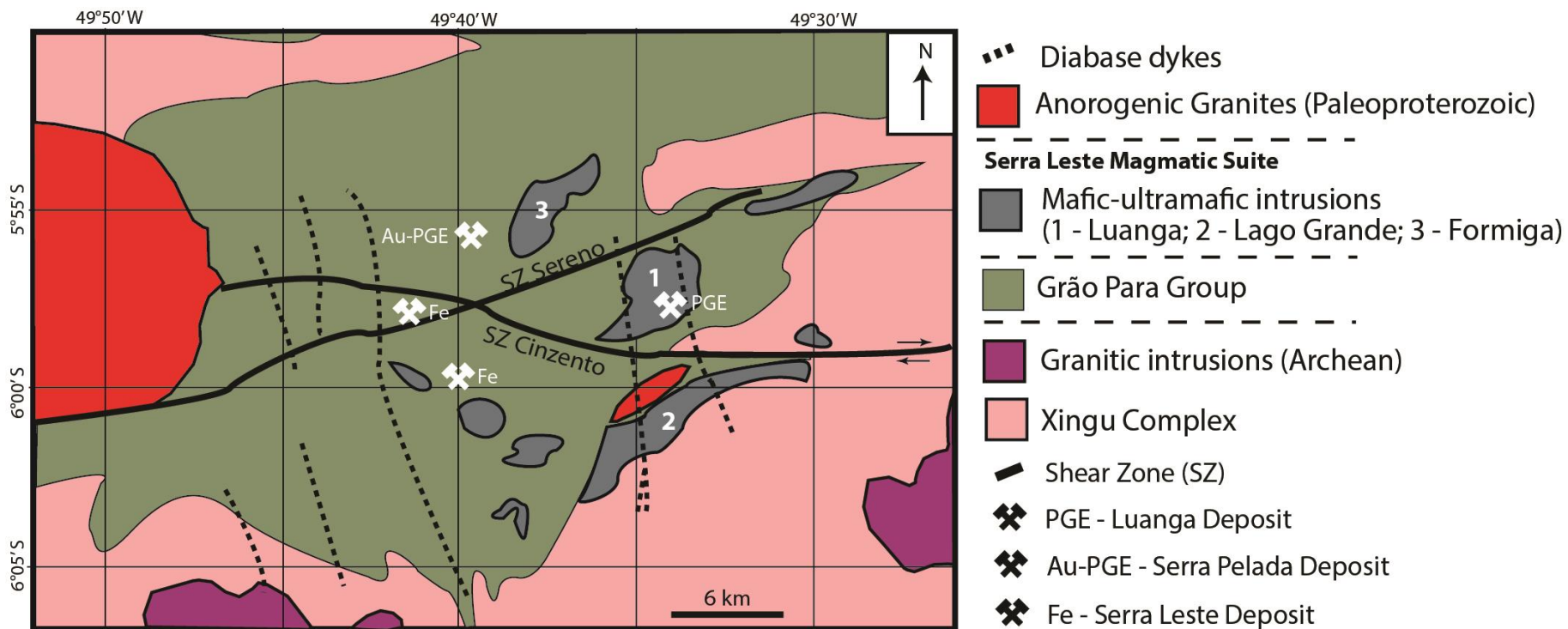
Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Geology, petrology and geochronology of the Lago Grande layered complex: Evidence for a PGE-mineralized magmatic suite in the Carajás Mineral Province, Brazil

Antonio Sales Teixeira ^a, Cesar Fonseca Ferreira Filho ^a,
Maria Emilia Schutesky Della Giustina ^{a,*}, Sylvia Maria Araújo ^a,
Heloisa Helena Azevedo Barbosa da Silva ^b



- Medium-sized layered intrusion 6 km long and up to 3.5 km wide.

- Magmatic layering is overturned with steep dip, suggesting an estimated thickness ~3.5 km in the widest central portion of the intrusion.
- Hosted by gneissic rocks (Xingu Complex) and metavolcanics (Grão Pará Group).
- Primary igneous textures are largely preserved, but the primary mineralogy is heterogeneously altered to greenschist to lower amphibolite metamorphic minerals.



Magmatic structure and stratigraphy of the Luanga Complex

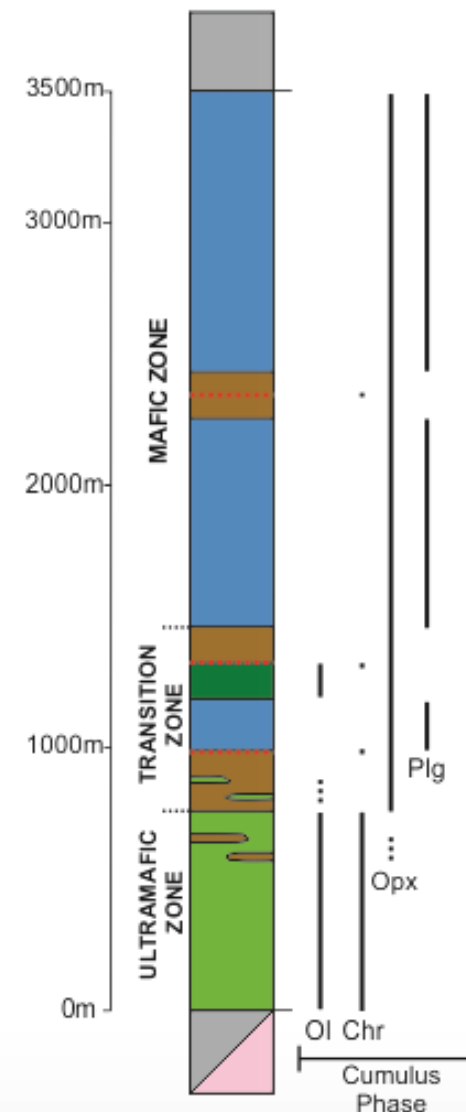
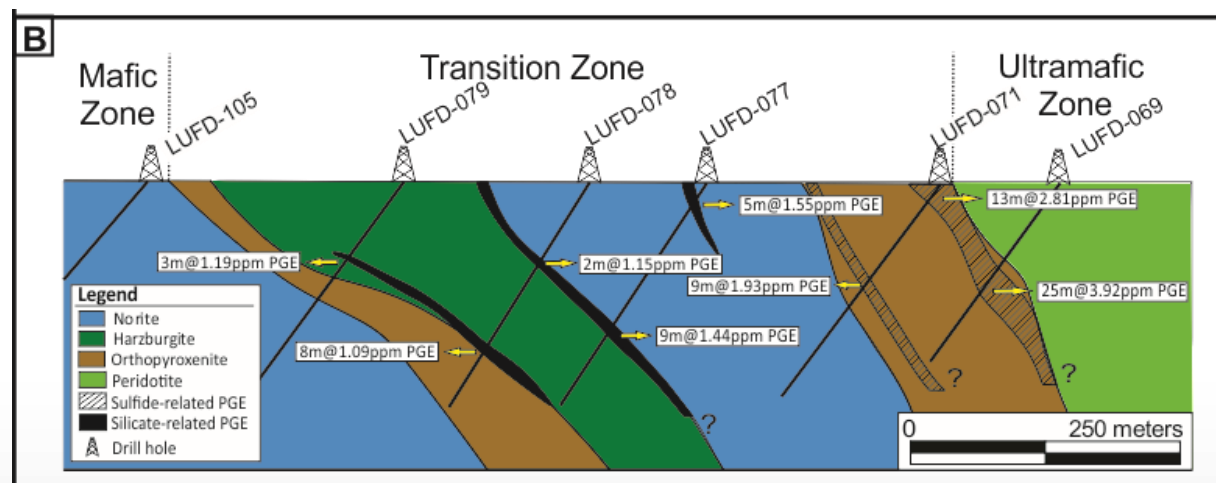
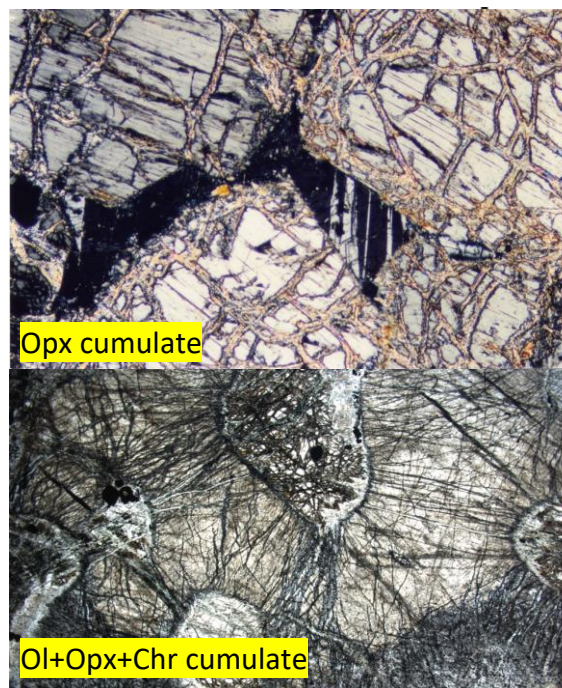
Stratigraphy:

Mafic Zone
Transition Zone
Ultramafic Zone

Crystallization Sequence



Opx+Pl
Opx
Opx+Chr
Ol+Opx+Chr
Ol+Chr



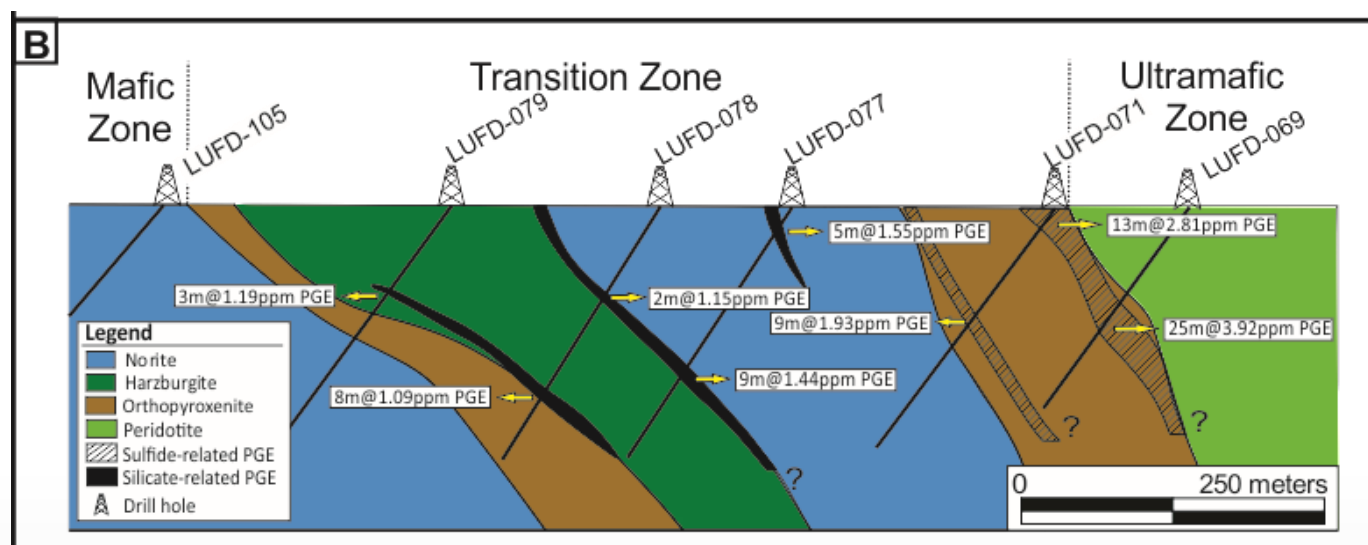
Modified from Ferreira Filho et al. (2007)

Luanga PGE-Ni-Cu deposit

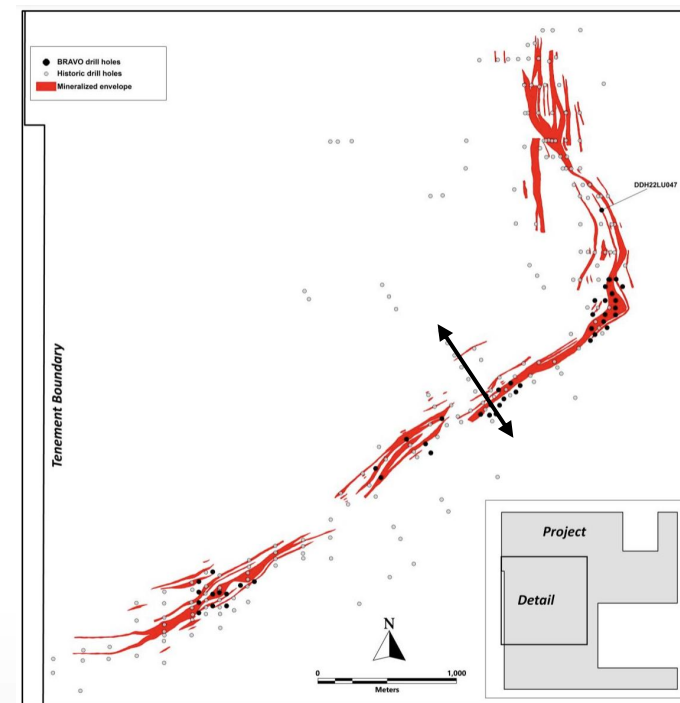
(142 Mt at 1.24 g/t PGE + Au and 0.11% Ni)

- The deposit is hosted in a 10–50 m thick stratabound zone of disseminated BMS (~1–5 vol%), designated Sulfide Zone, located along the contact of the Ultramafic and Transition zones.
- This mineralized interval extends along the entire length of the intrusions (~3 km). Resources were evaluated for a shallow (~250 meters deep) open pit. Untested for deep resources.

Apart from the Sulfide Zone, several PGE-mineralized intervals occur in the Luanga Complex. These include different styles of PGE mineralization:



Modified from Ferreira Filho et al. (2007)



BRAVO – News Release – Oct 2022

Luanga PGE-Ni-Cu deposit Sulfide Zone

Pl Orthopyroxenite
with interstitial BMS (Pn+Po+Ccp)



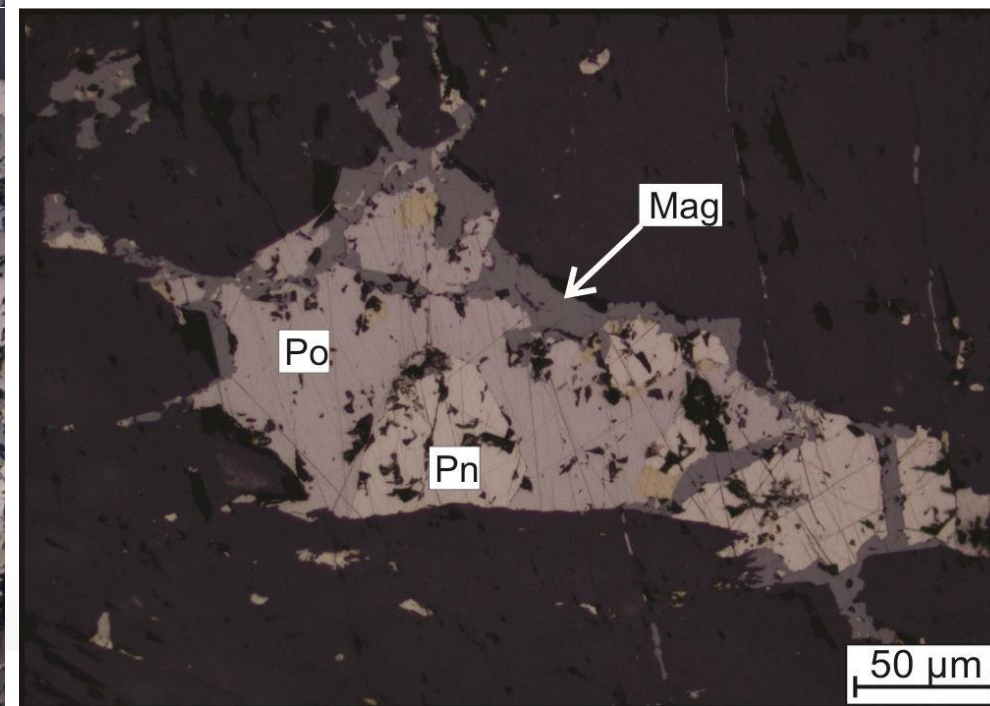
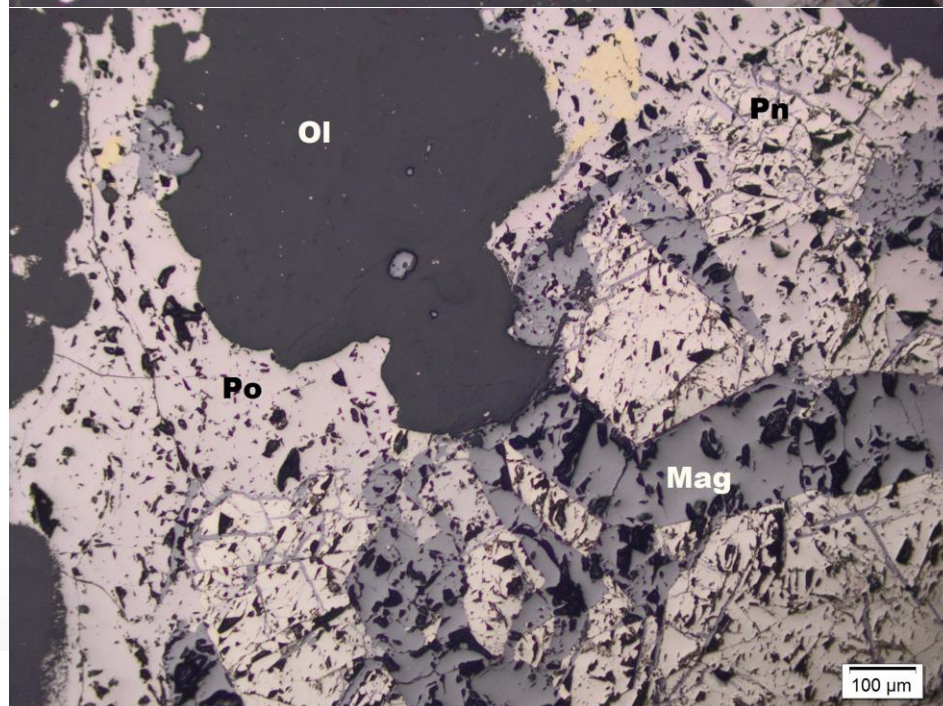
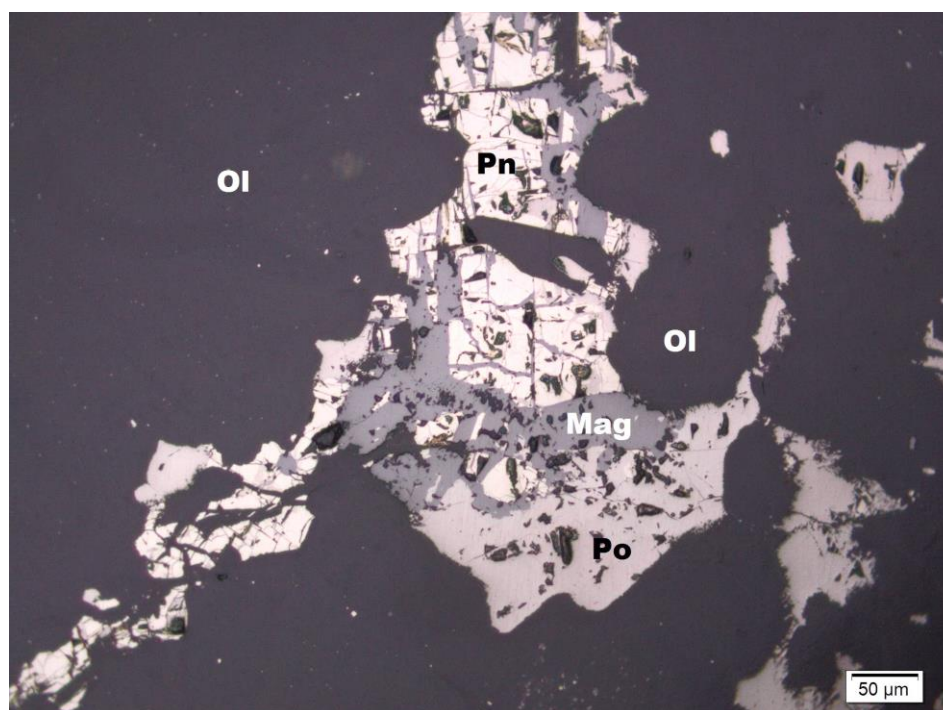
Harzburgite
with interstitial BMS (Pn+Po+Ccp)



- Nicely preserved magmatic textures.
- Typical PGE-Ni-Cu mineralization originated by the segregation of an immiscible sulfide liquid.

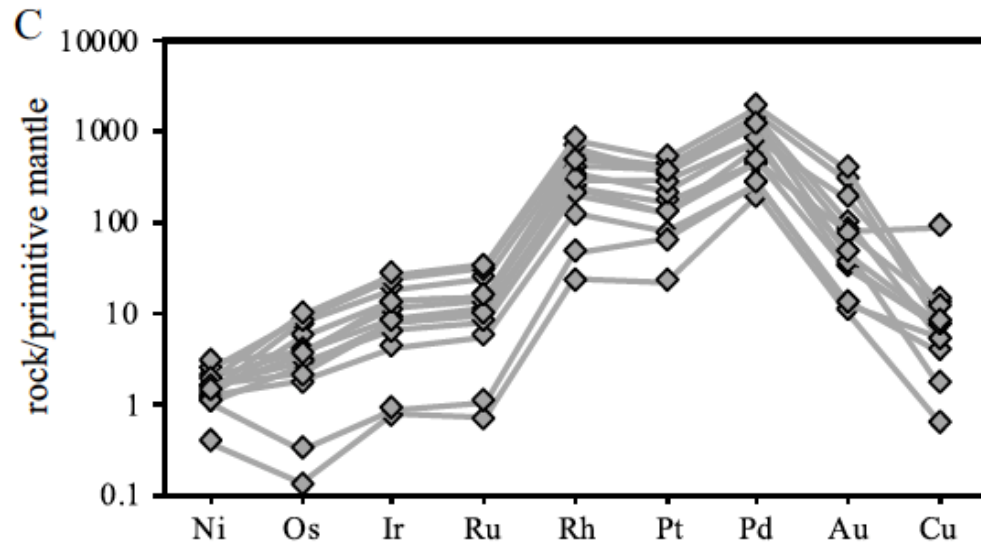
Luanga PGE-Ni-Cu deposit Sulfide Zone

- Typical PGE mineralization originated by the segregation of an immiscible sulfide liquid.
- Sulfide blebs interstitial to silicates.
- Primary BMS and PGM are heterogeneously altered.
- $Pn \sim Po \gg Ccp$

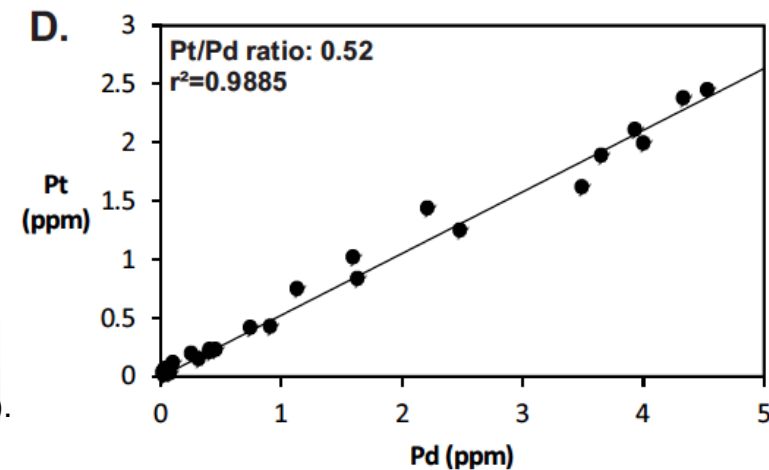
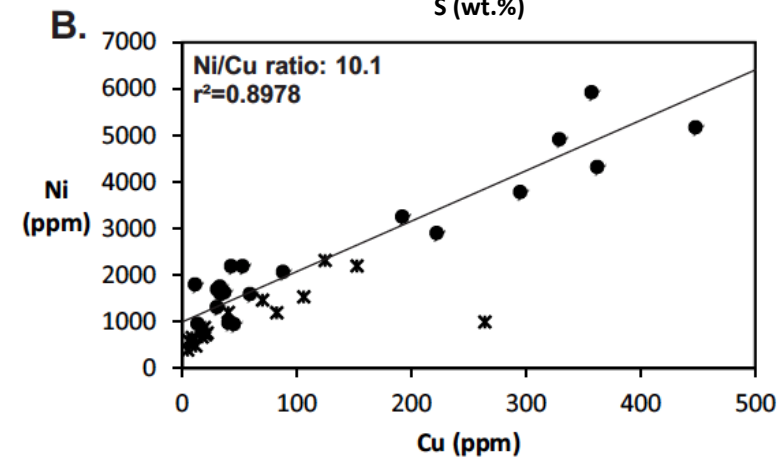
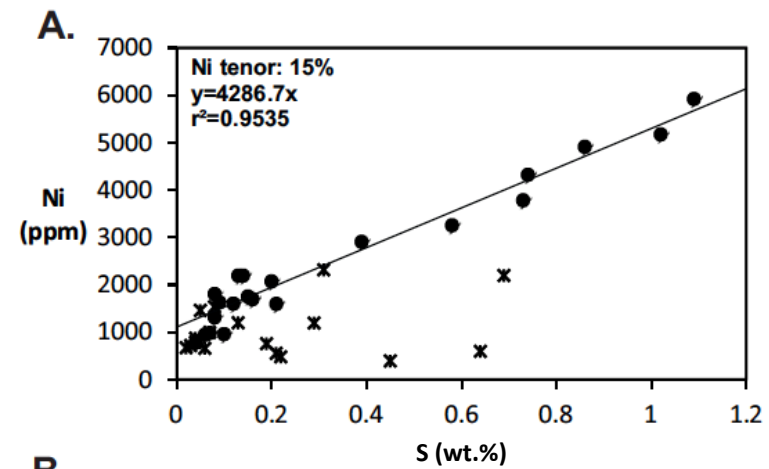


Luanga PGE-Ni deposit Sulfide Zone

- High Ni tenors (15 wt%)
- High Ni/Cu ratios (10)
- Pt/Pd ratios < 1 (0.52)
- Very high PPGE tenors (Pd ~ 150 ppm)
- PPGE-enriched mantle-normalized patterns. Similar to most reef-type PGE deposits (e.g., Bushveld).

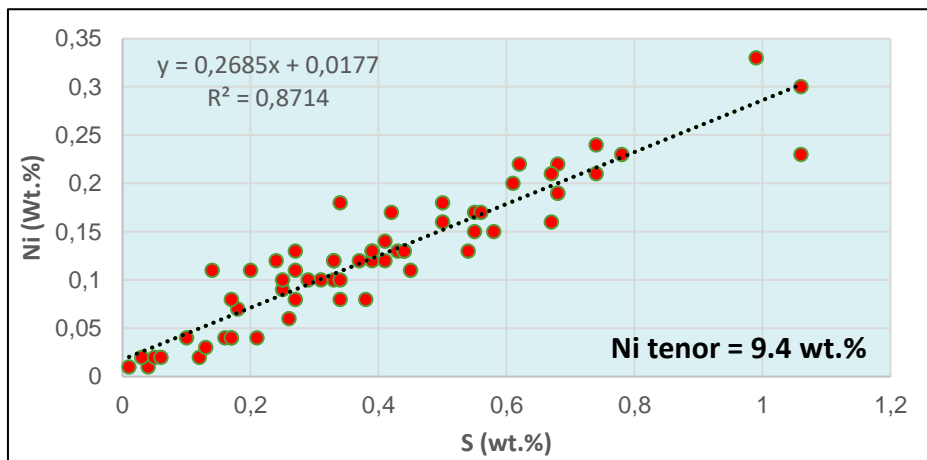


Mansur et al., 2020; 2021).



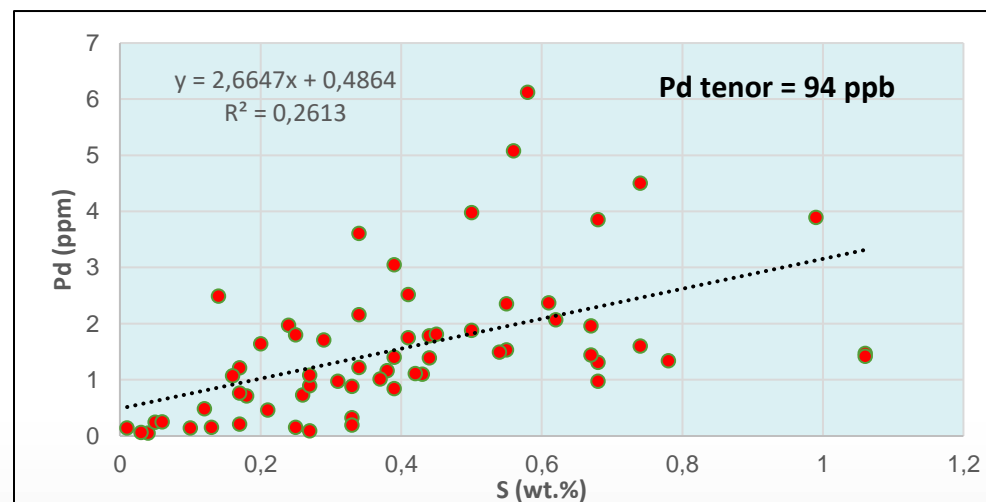
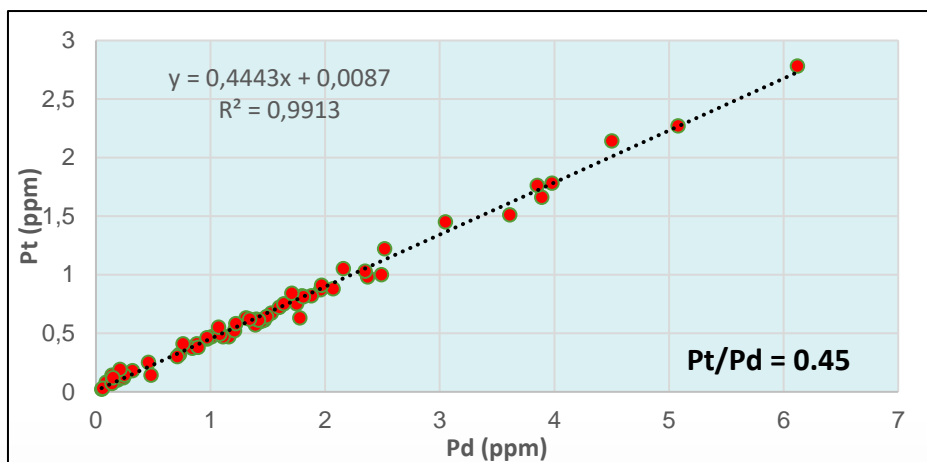
Luanga PGE-Ni deposit Sulfide Zone

LUFD-019



Previous results are generally supported by new exploration data (BRAVO)

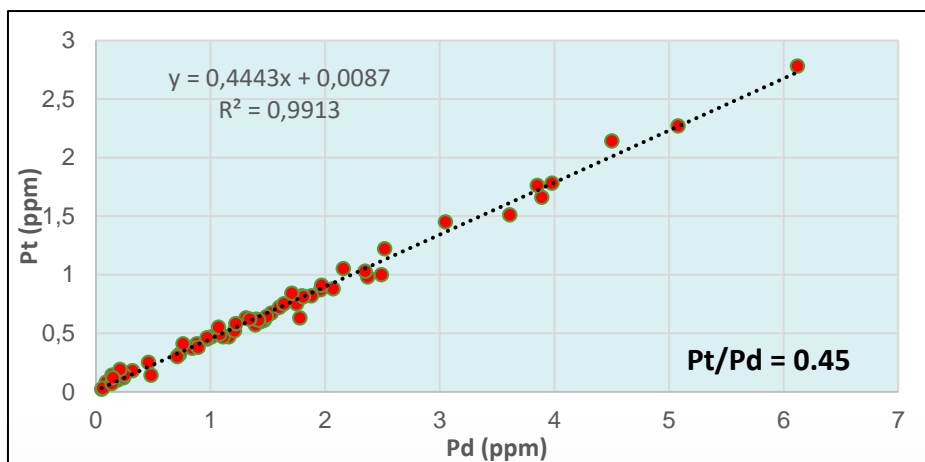
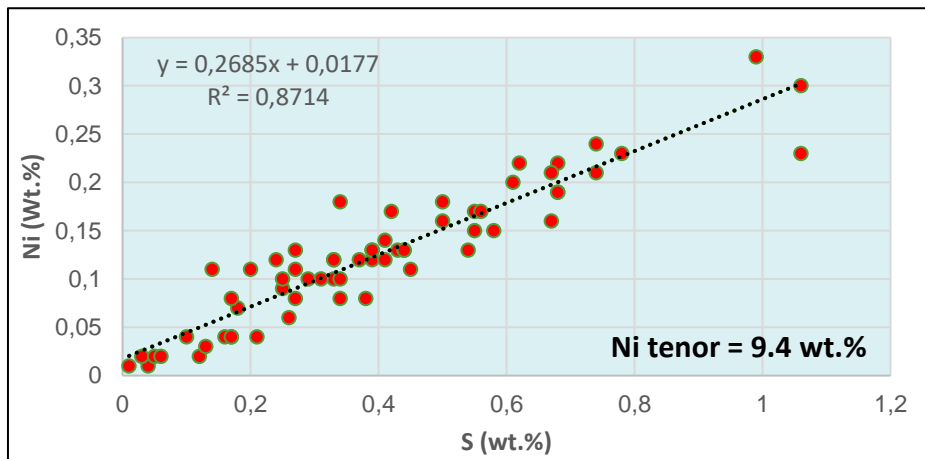
- High Ni tenors (but variable)
- High Ni/Cu ratios (but highly variable)
- Pt/Pd ratios ~ 0.5
- Poor S-PGE correlation and very high PPGE tenors



Data from BRAVO (2022)

Luanga PGE-Ni deposit Sulfide Zone

LUFD-019

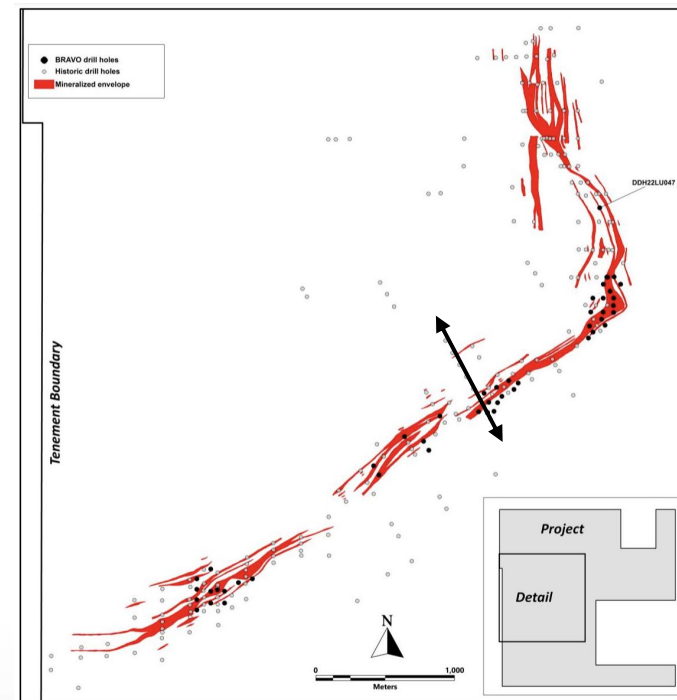


Data from BRAVO (2022)

Previous results are generally supported by new exploration data (BRAVO).

New questions:

- How Ni-PGE tenors and Pt/Pd are impacted by alteration?
- How Ni-PGE tenors and Pt/Pd vary along (3 km) and across (10-50 m) the Sulfide Zone?

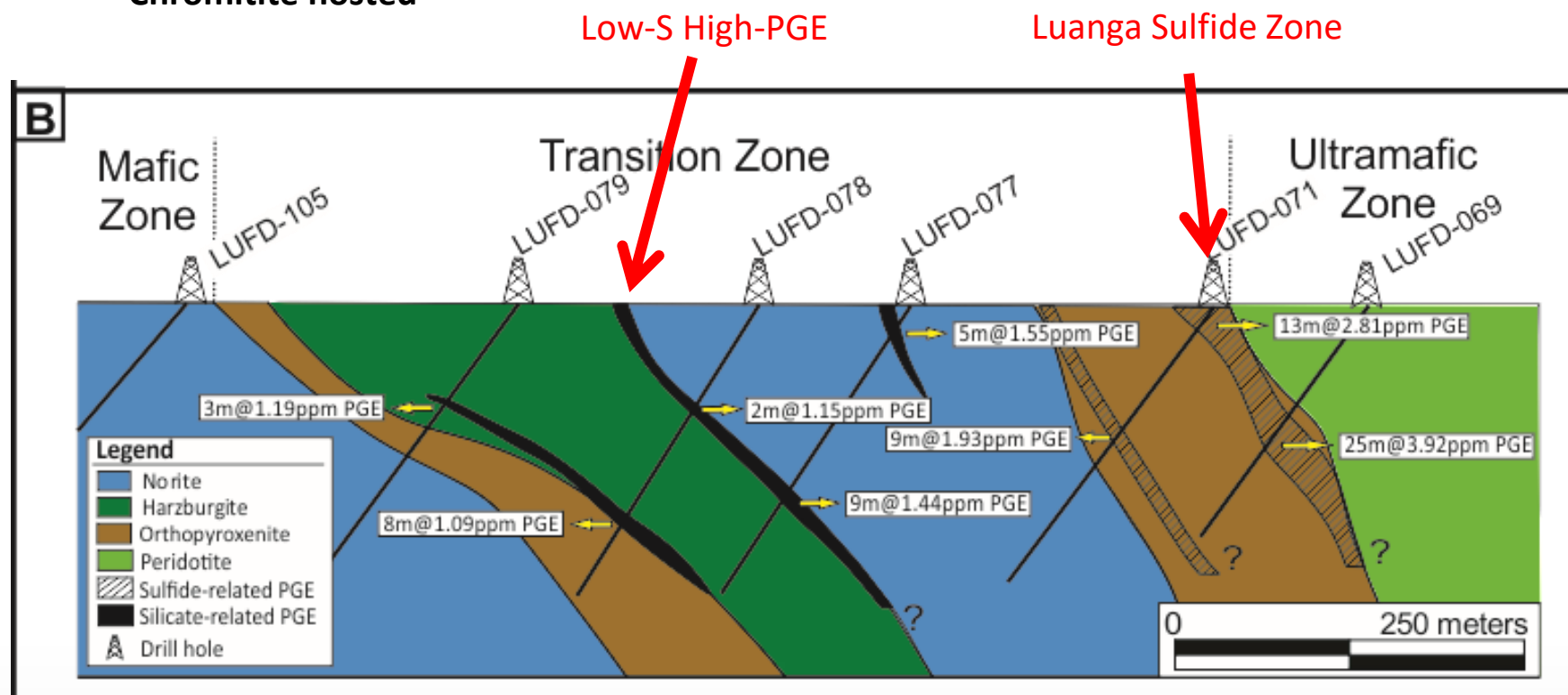


BRAVO – News Release – Oct 2022

Luanga low-S high-PGE mineralization

Apart from the Sulfide Zone, several PGE-mineralized intervals occur in the Luanga Complex. These include different styles of PGE mineralization:

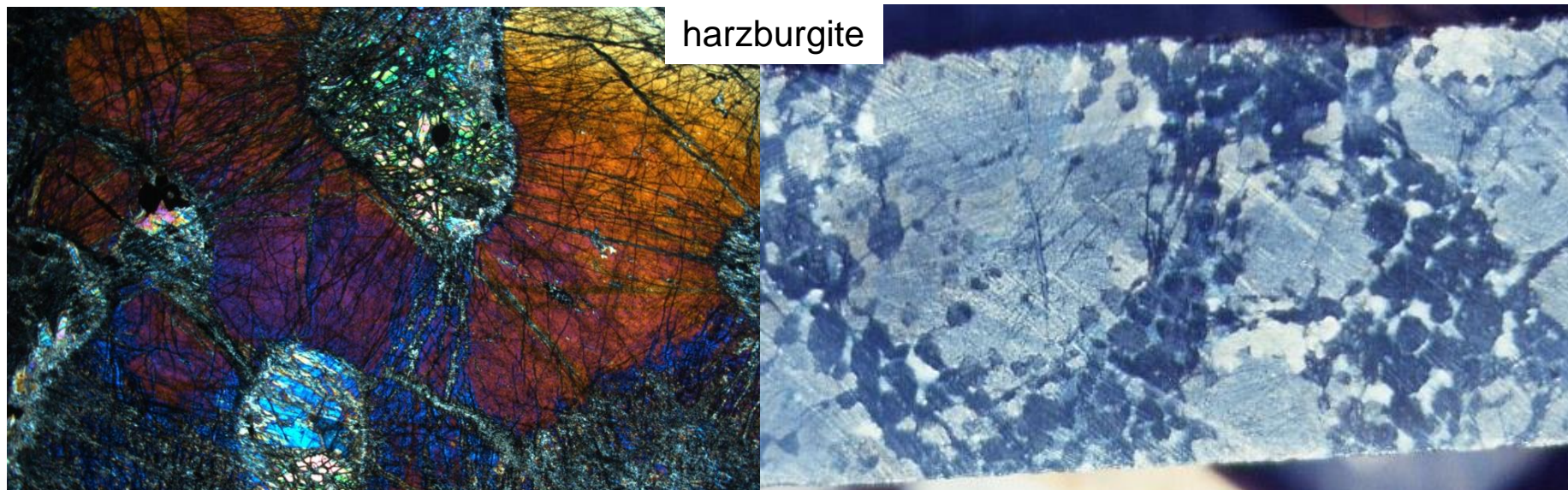
- **Low-S high-PGE**
- **Chromitite hosted**



Modified from Ferreira Filho et al. (2007)

Luanga low-S high-PGE mineralization

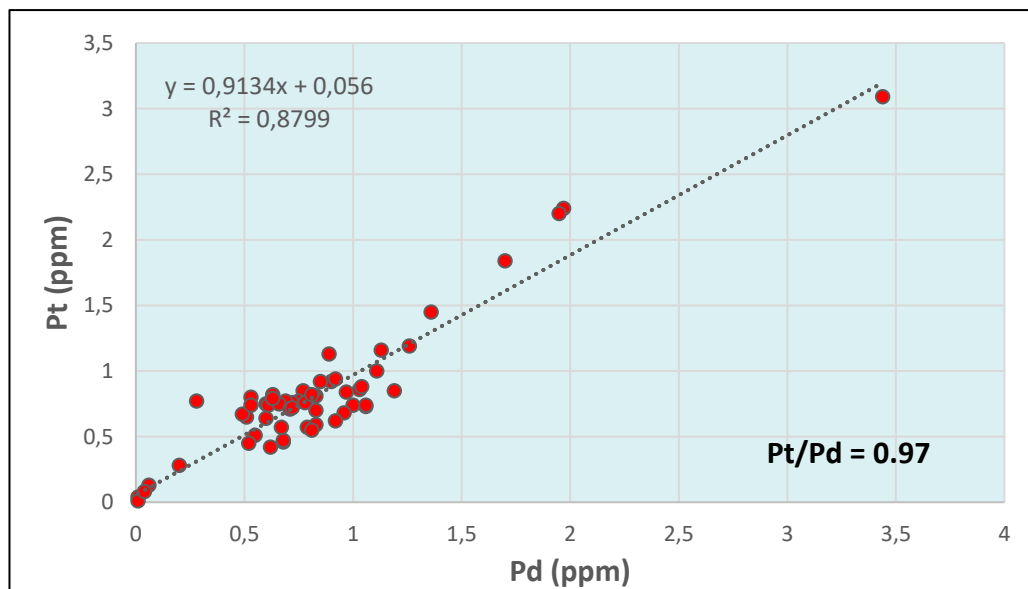
- Low-S-high-PGE zones have no distinctive petrographic features. They are associated with Ni-rich olivine and Opx, without association with BMS and/or chromite.
- How this type of PGE mineralization originates?
- How geochemical and mineralogical features of low-S high-PGE zones compare with the Sulfide Zone?



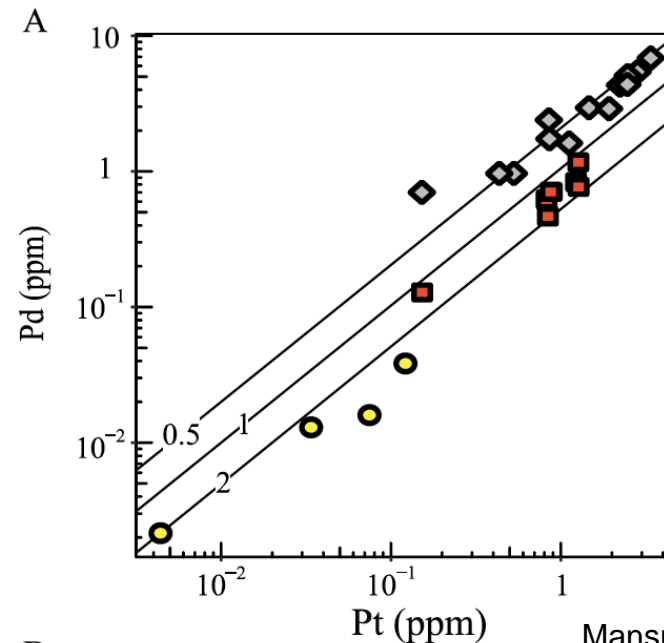
Luanga low-S high-PGE mineralization

- Pt/Pd ratios > 1 (1-2)
- PPGE-enriched mantle-normalized patterns. Similar to the Sulfide Zone except for Pt/Pd ratio and overall lower contents

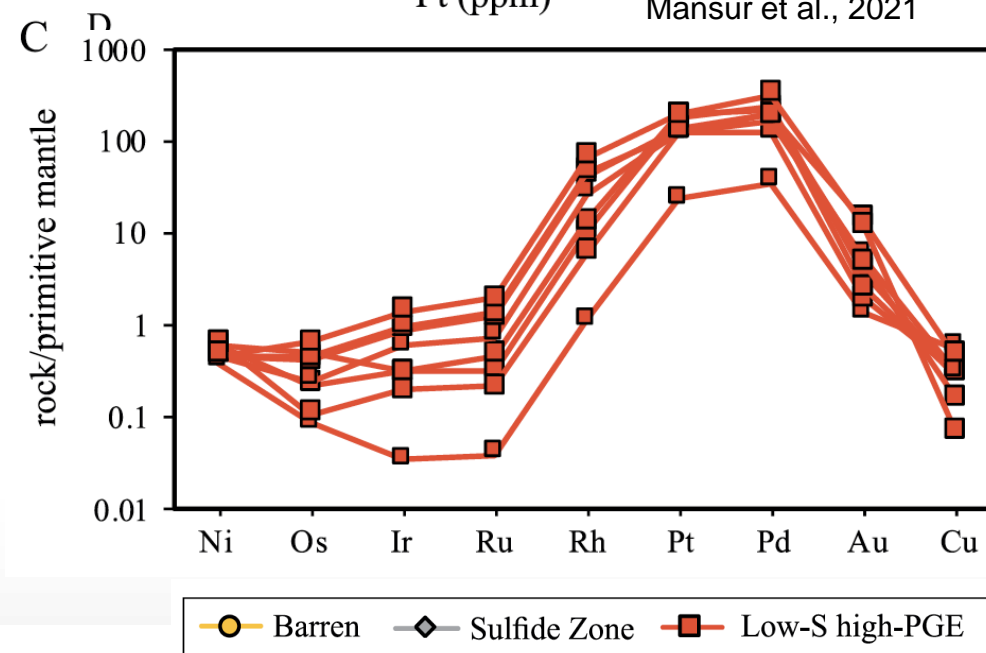
LUF0-019



Data from BRAVO (2022)



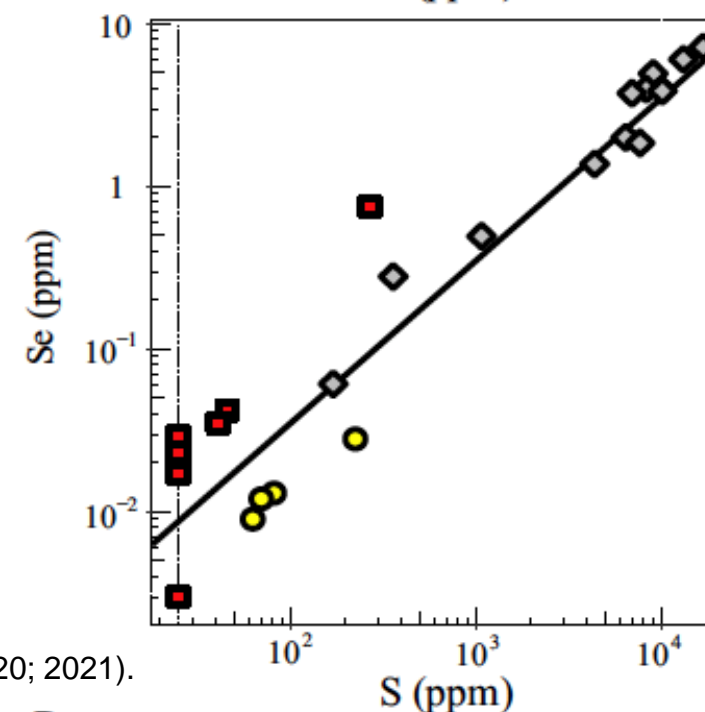
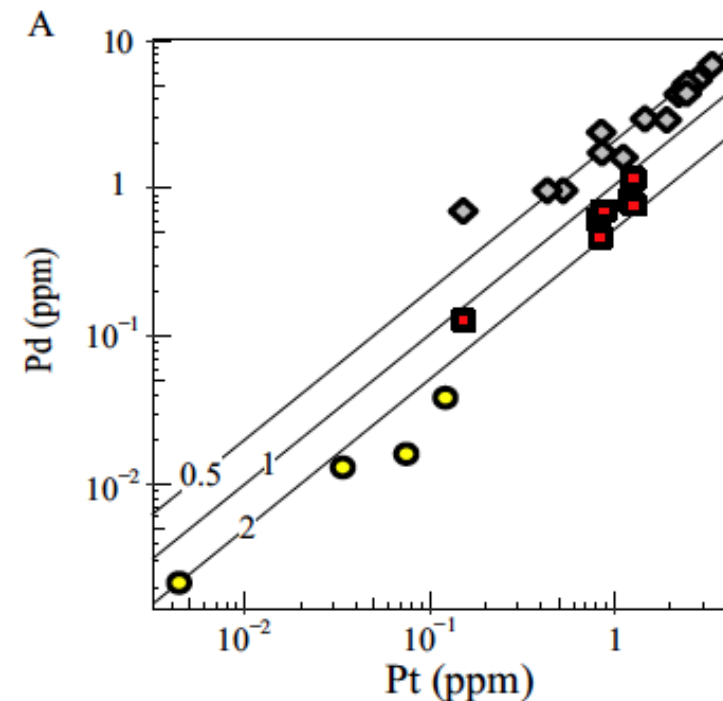
Mansur et al., 2021



Luanga PGE-Ni deposit

low-S high-PGE zones

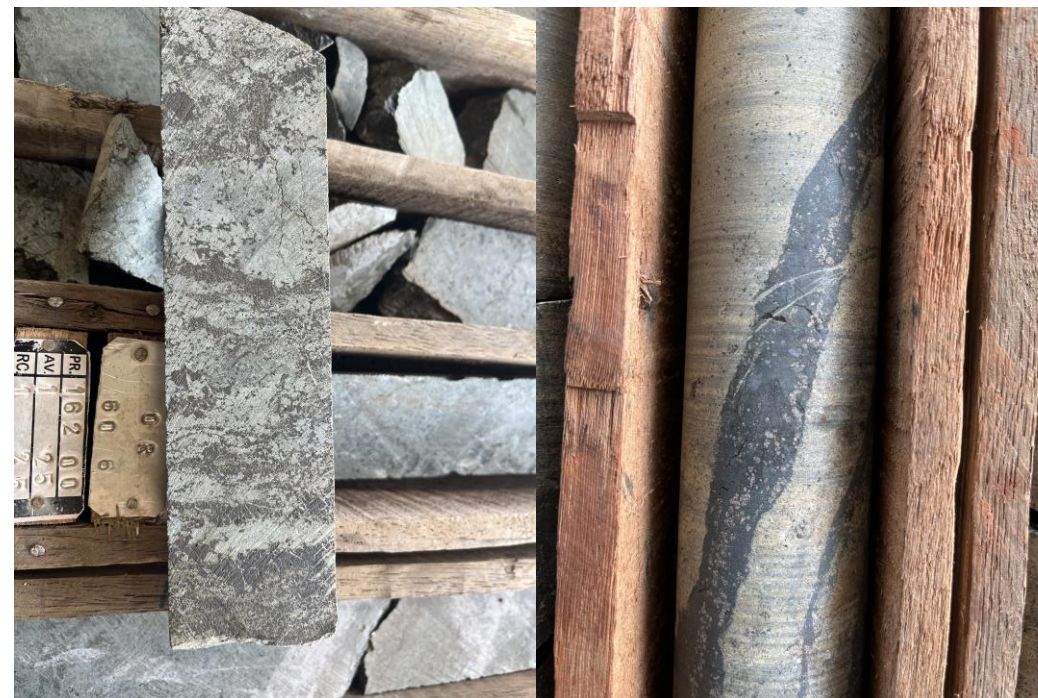
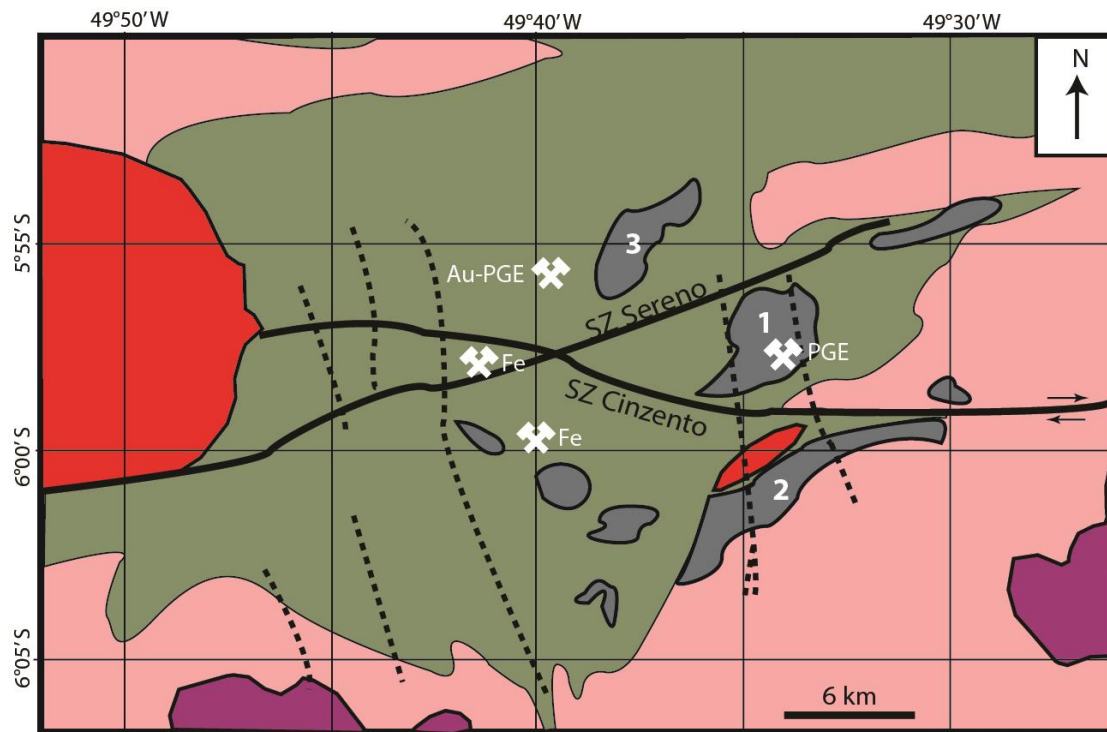
- Pt/Pd ratios of the Sulfide Zone (~ 0.5) and low-S-high-PGE zones (~ 1 -2) are different.
- S/Se ratios of the Sulfide Zone are similar to values for mantle derived S (~ 3000), while lower ratios for the low-S-high-PGE zones are commonly interpreted as the result of S loss during alteration.
- Our results support that S, PGE and TABS are variably remobilized during alteration of the Luanga Ni-Cu-PGE Deposit.
- The low-S high-PGE zones is interpreted as an event of segregation of an immiscible sulfide liquid followed by S loss during post-magmatic alteration (Mansur et al. 2021).
- Low-S high-PGE intervals are not distinctively altered. What type of alteration?



Mansur et al., 2020; 2021).

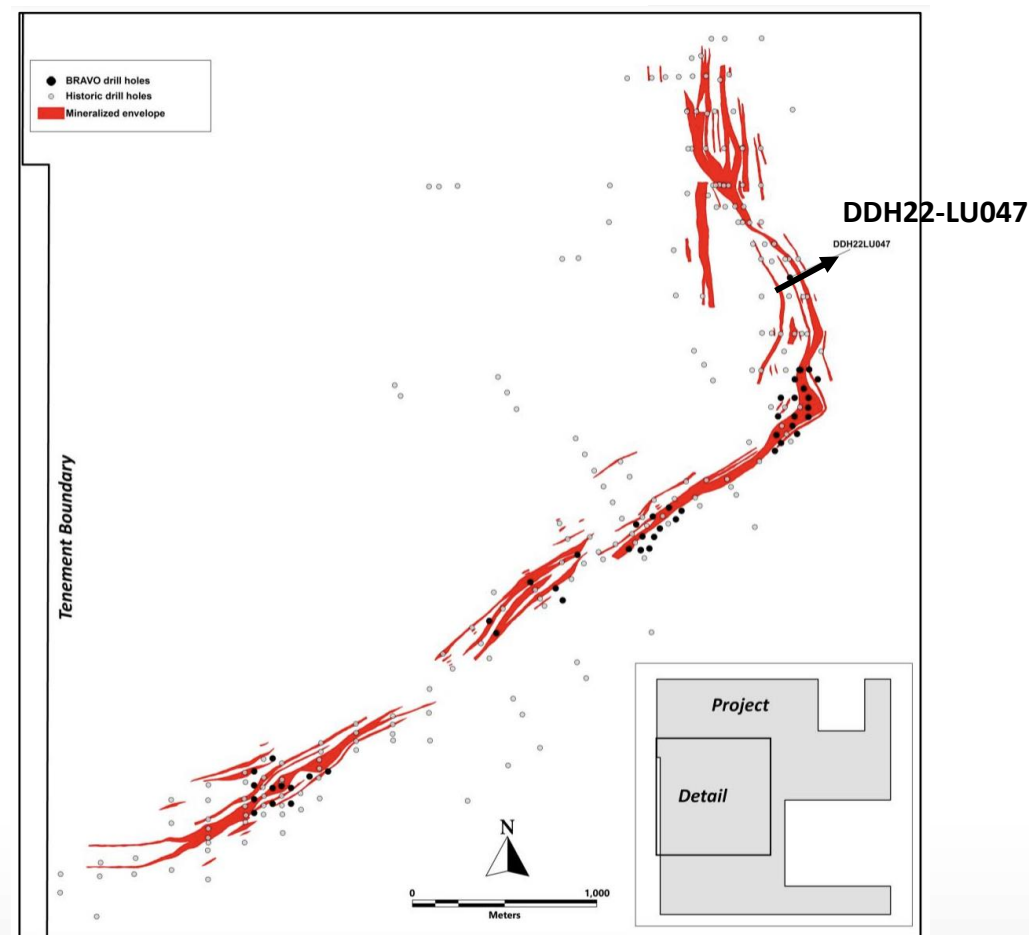
What type of alteration?

- Intersections of banded rocks consisting of amphibole (hbl or grunerite), magnetite and garnet, located at the northwestern section of the Luanga Complex, are interpreted to result from localized IOCG type hydrothermal alteration.
- How this alteration impact the primary magmatic PGE-Ni-Cu sulfide ore in the Luanga Complex?
- Is it possible that the alteration of magmatic sulfide deposits may have led to the origin of Ni-rich (e.g., Jaguar) and Au-PGE (e.g., Serra Pelada) hydrothermal deposits in Carajás?



How do the massive sulfide ores fit in?

HOLE-ID	From (m)	To (m)	Thickness (m)	Pd (g/t)	Pt (g/t)	Rh (g/t)	Au (g/t)	PGM + Au (g/t)	Cu (%)	Ni (%) (Sulphide)	Type
DDH22LU047	131.11	142.15	11.04	3.56	0.57	0.07	0.04	4.24	1.23	2.04	FR



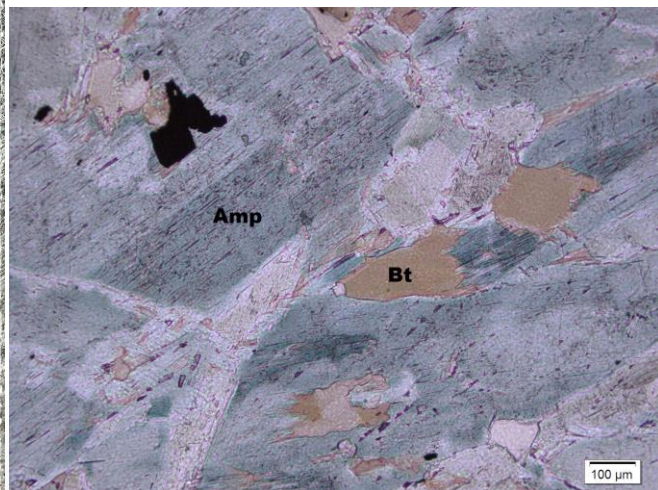
How do the massive sulfide ores fit in?

MASU - Host rocks

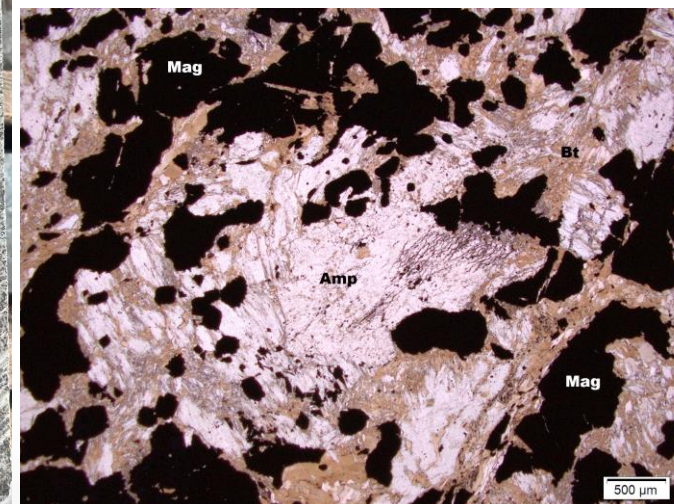
- MASU were intersected at the northern section of the intrusion. The footwall consists of amphibolitite and amphibole-magnetite-rich rocks, with variably altered orthopyroxenite and norite in the hangingwall.
- MASU are hosted by amphibolitites interpreted as metasomatic rocks (Hbl+Mag+Bt alteration).



Amphibolitite

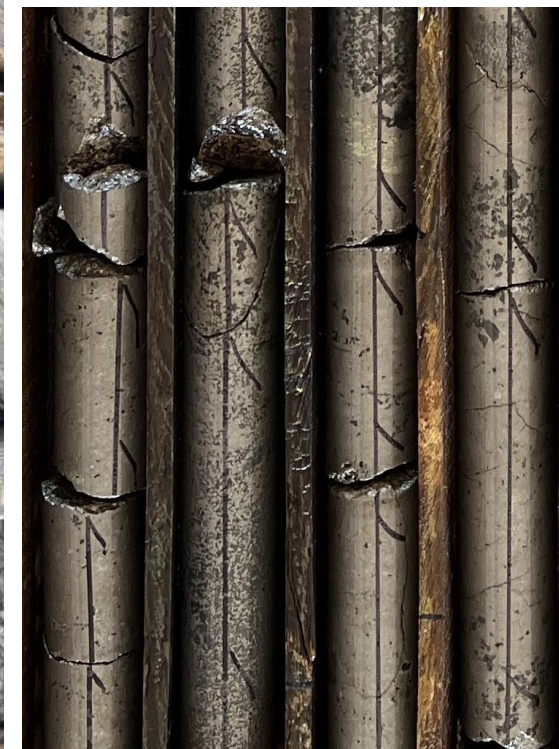
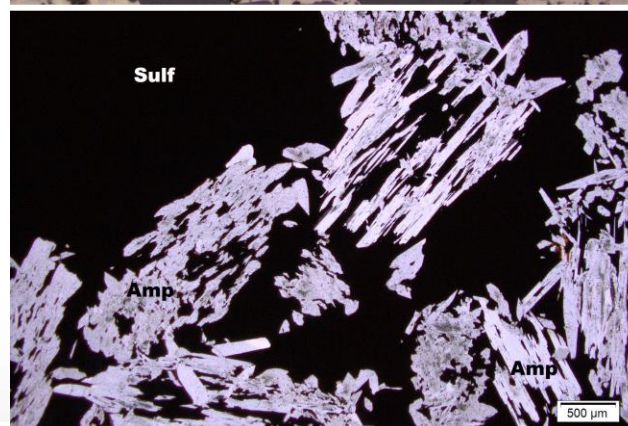
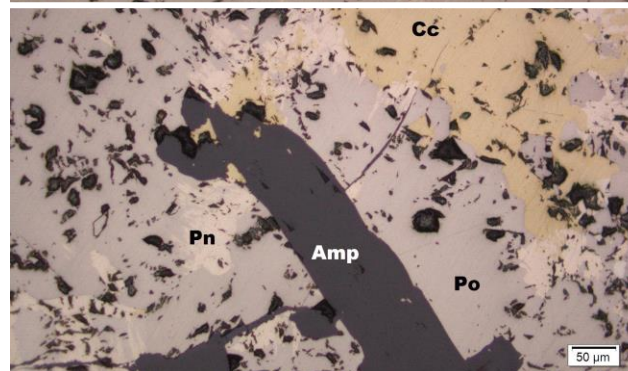
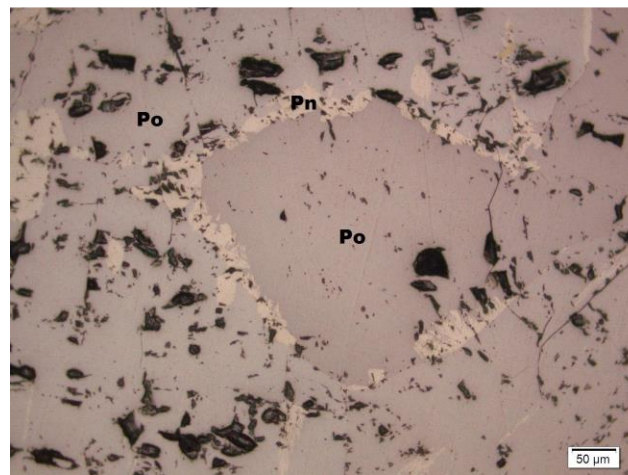


Banded magnetite amphibolitite



MASU - Textures and mineralogy

- Sulfides consists mainly of Po-Pn with associated Ccp-rich domains (from few centimeters up to 0.5 m).
- Po (~80-90%) occurs as a medium-grained aggregate with associated fine-grained Pn (~10-20%) and irregular domains with abundant Ccp.
- Sulfides are associated with variable proportions of medium-grained dark green amphiboles and minor biotite, magnetite, and quartz.

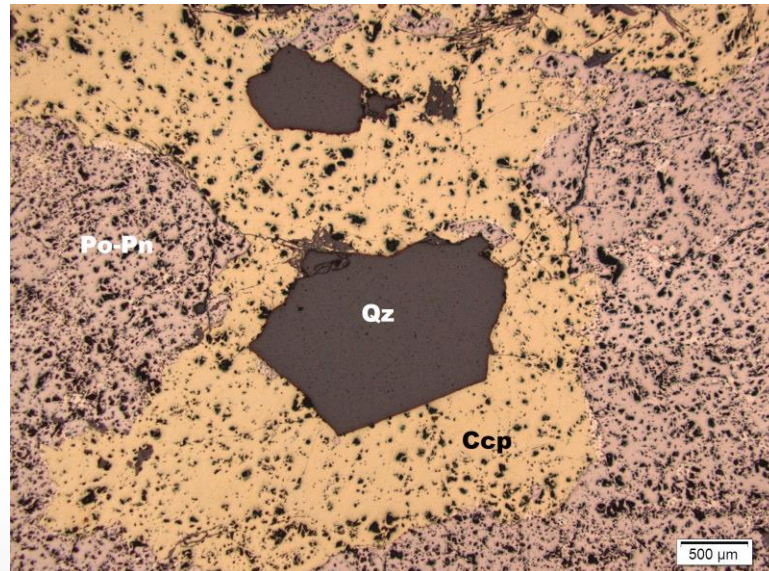
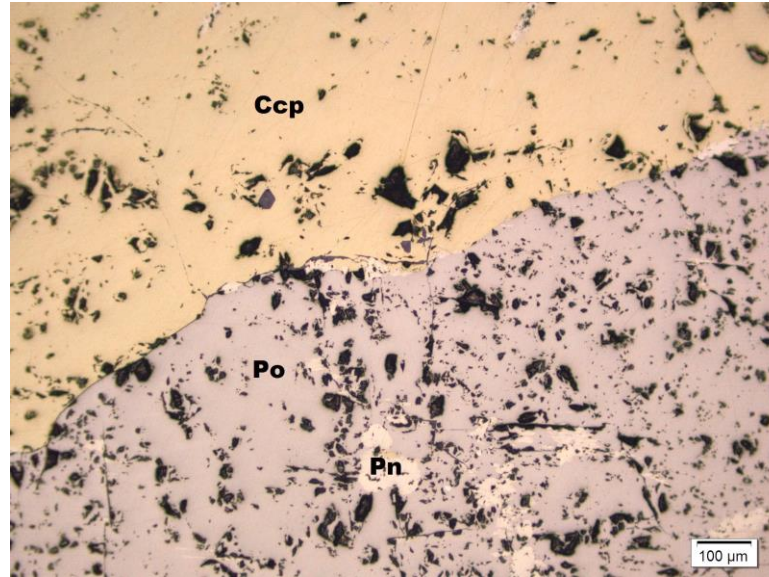


Po-Pn-rich domain

How do the massive sulfide ores fit in?

MASU - Textures and mineralogy

- Sulfides consists mainly of Po-Pn with associated Ccp-rich domains (from few centimeters up to 0.5 m).
- Po (~80-90%) occurs as a medium-grained aggregate with associated fine-grained Pn (~10-20%) and irregular domains with abundant Ccp.
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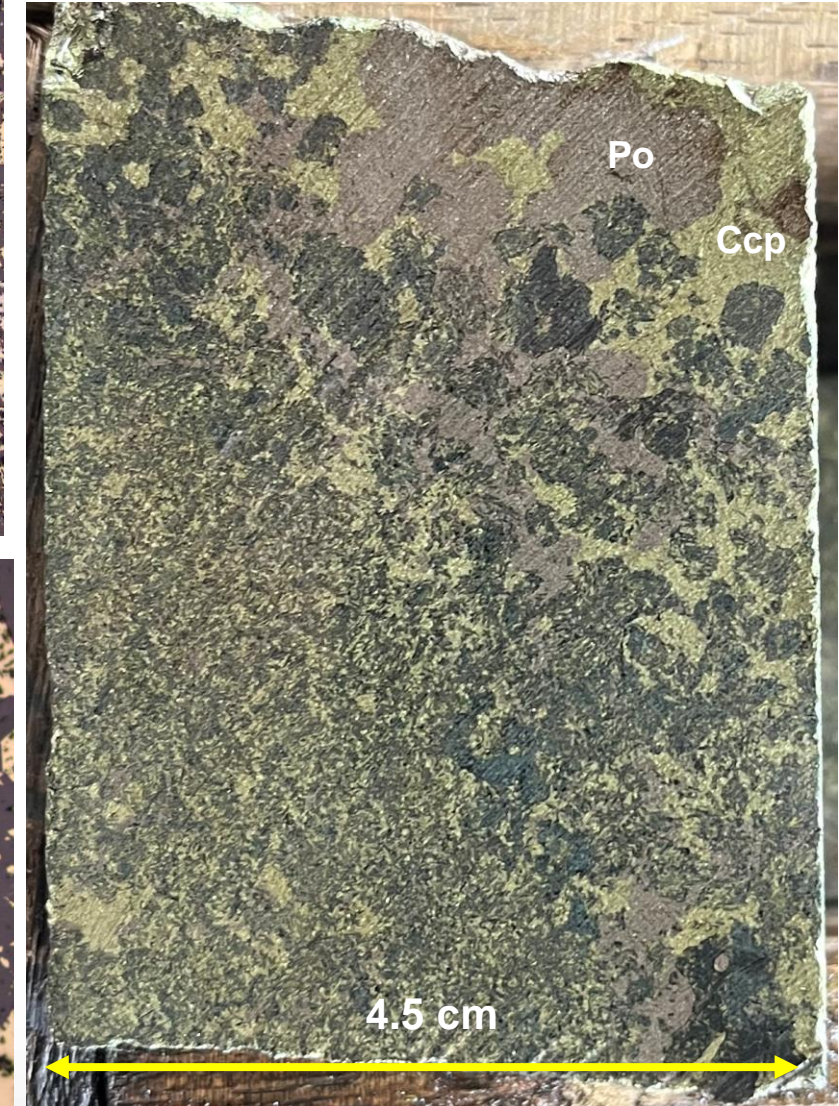
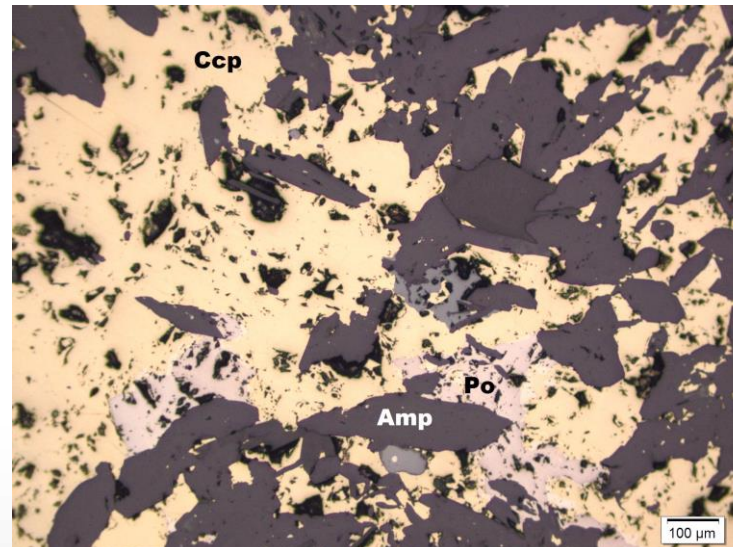
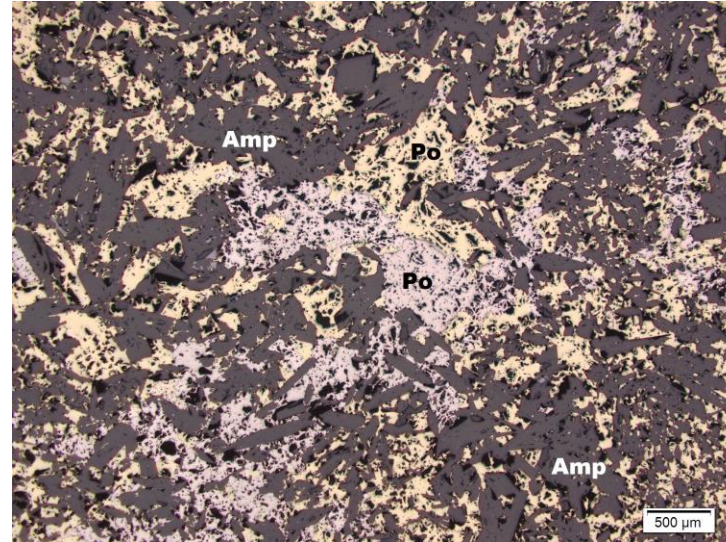


How do the massive sulfide ores fit in?

Ccp-rich domain

MASU - Textures and mineralogy

- Sulfides consists mainly of Po-Pn with associated Ccp-rich domains (from few centimeters up to 0.5 m).
- Po (~80-90%) occurs as a medium-grained aggregate with associated fine-grained Pn (~10-20%) and irregular domains with abundant Ccp.
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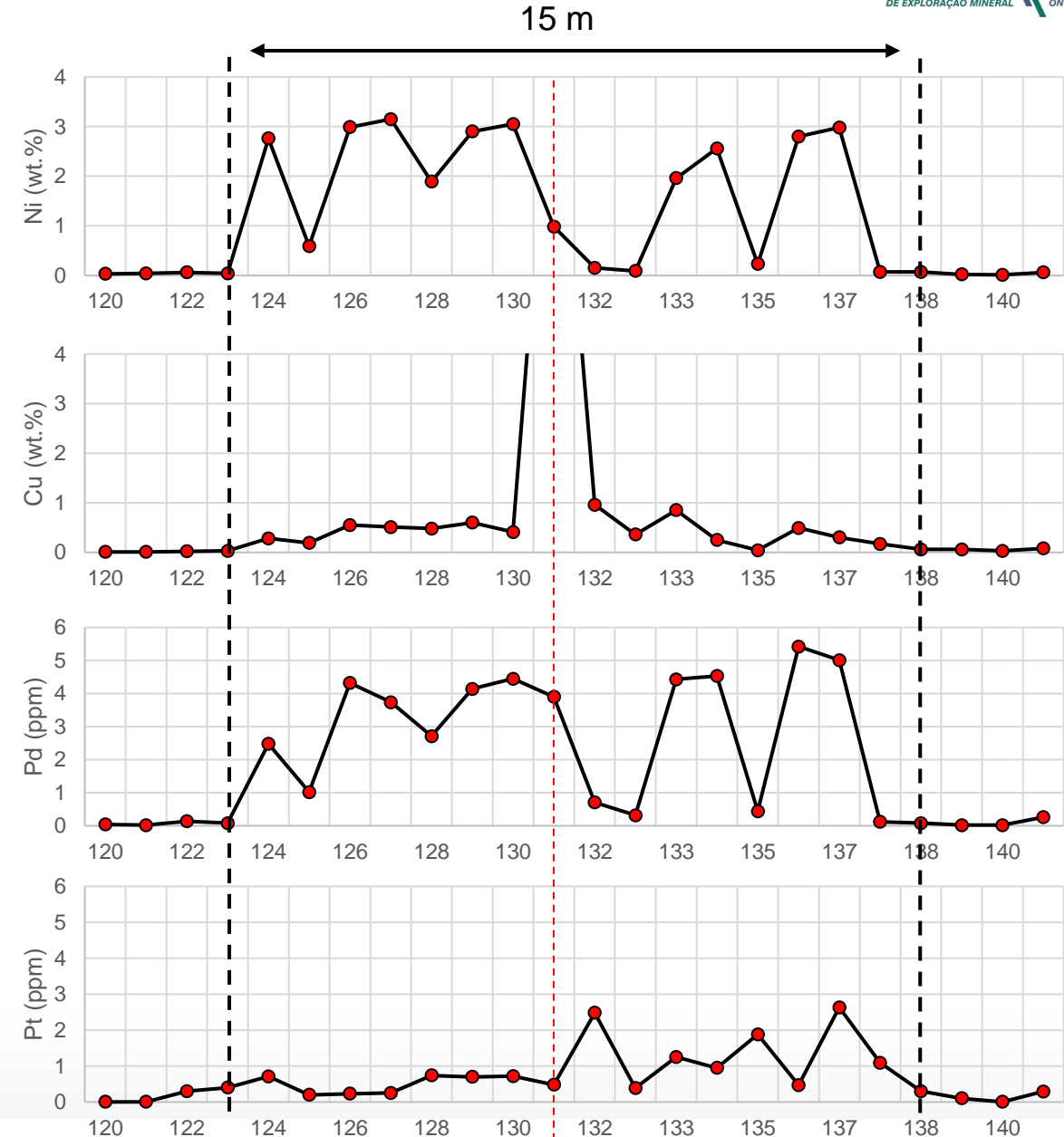


How do the massive sulfide ores fit in?

MASU - Chemical composition

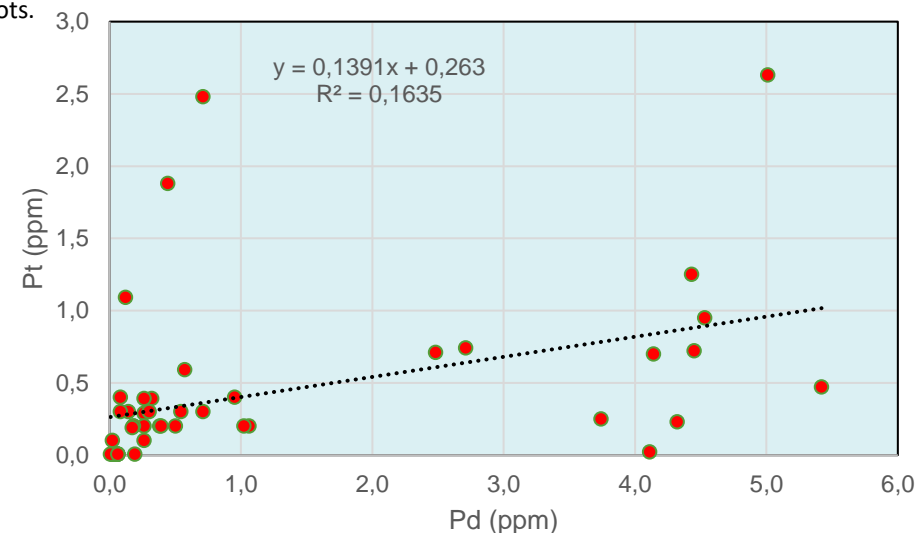
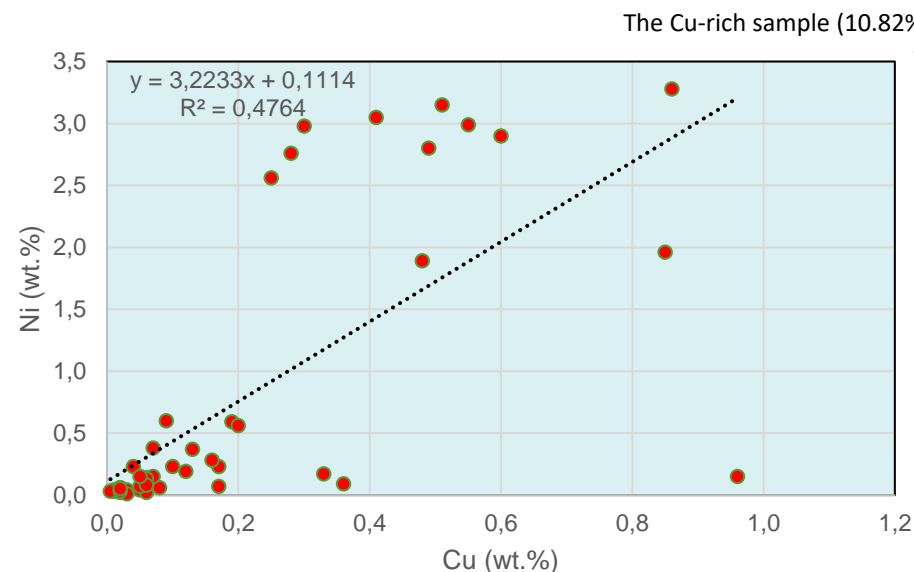
- Results available to date: Ni, Cu, Co, Pt, Pd, Au
- The massive sulfide interval has variable contents of Ni and Cu, generally Ni>Cu, and weak Ni-Cu correlation. One Cu-rich interval has up to 10.82% Cu and 0.98% Ni.
- The massive sulfide interval has variable contents of Pt and Pd, generally Pd>Pt, and very weak positive Pd-Pt correlation.
- Except for the high positive correlation of Ni and Pd, positive correlation of Pt with Cu and Ni, and Pd with Cu is very weak.
- Co contents have a very high correlation with Ni, suggesting that Co is mainly contained within Pn.

Data from BRAVO (2022)



How do the massive sulfide ores fit in?

MASU - Chemical composition



The massive sulfide interval has variable contents of Ni and Cu, generally Ni>Cu, and weak Ni-Cu correlation.

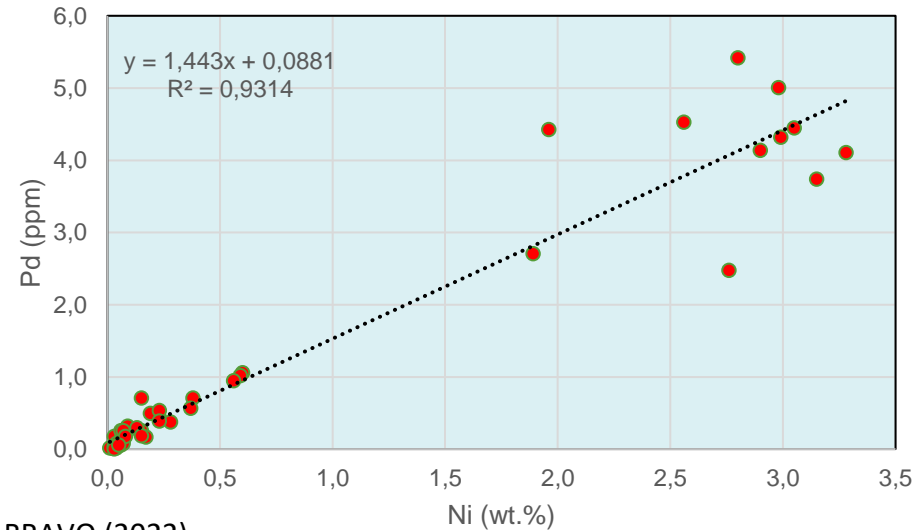
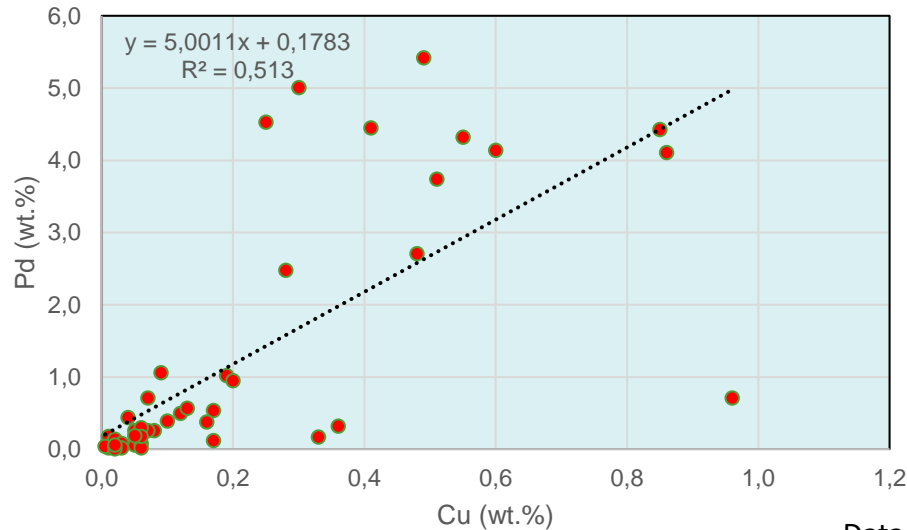
Sulfur analyses are not available for tenor calculation. Analyses of the most massive Po-Pn rich samples suggest moderate Ni (~3 wt.%) and Cu (~0.5 wt.%) tenor, with low Pd (4-5 ppm) and Pt (1-3 ppm) tenors.

The massive sulfide interval has variable contents of Pt and Pd, generally Pd>Pt, and very weak positive Pd-Pt correlation.

Cu-rich samples do not have higher Pt-Pd contents.

How do the massive sulfide ores fit in?

MASU - Chemical composition

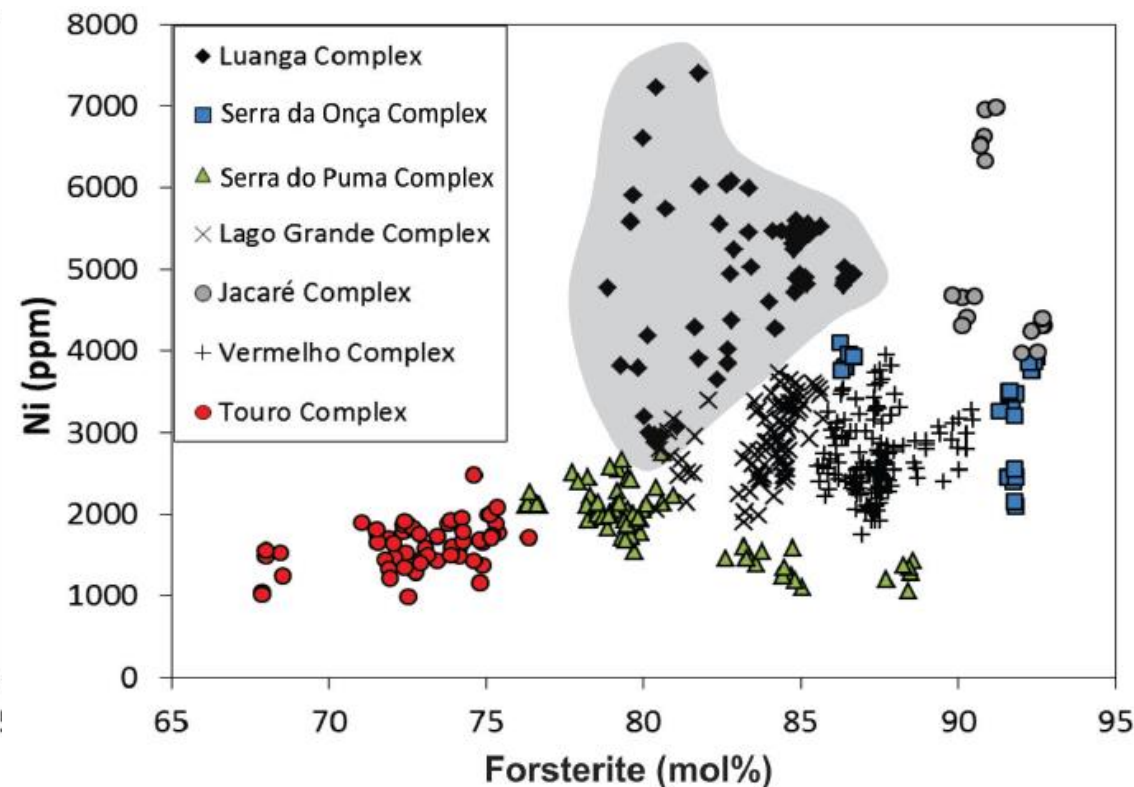
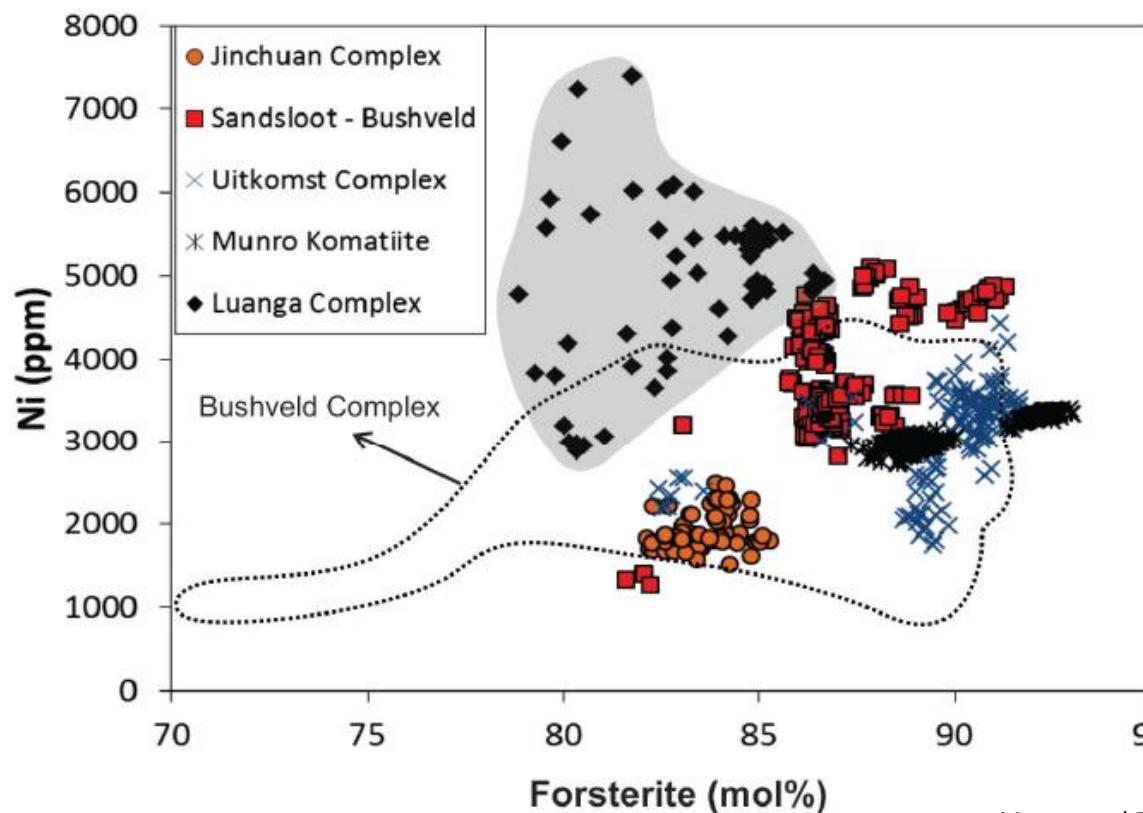


Data from BRAVO (2022)

- Except for the high positive correlation of Ni and Pd, positive correlation of Pd with Cu and Ni, and Pd with Cu is very weak.
- Note however that correlation is mainly controlled by samples with disseminated sulfides (i.e., low Ni and Cu contents). Correlation of Cu and Ni with Pd is very low for MASU samples.
- Higher Pd contents for samples with high nickel suggests that Pd is mainly contained within Pn.

Olivine Compositions

- Olivine in the Luanga Complex ($\text{Fo}_{78.9-86.4}$) is moderately primitive and has significantly higher Ni content (up to 7500 ppm) than most layered intrusions
- Ni contents in the Luanga Complex stand among the highest values ever reported in layered intrusions, except for the Kevitsa intrusion (Yang et al. 2013).



How Ni-rich magmas are formed?

- Generation of magmas from pyroxenitic mantle sources (Sobolev et al., 2005; 2007). Produces moderate Ni enrichment (1.5 to 2 times).
- Upgrading of magmas through dissolution of previously formed Ni-rich sulfide melts (Kerr and Leitch, 2005). In the "Multistage-dissolution upgrading model both Ni and PGE are enriched (e.g., Kevitsa Ni-Cu-PGE deposit; Yang et al. 2013).

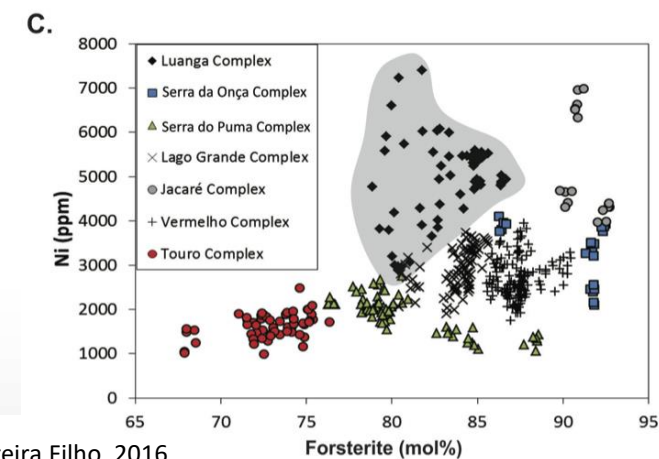
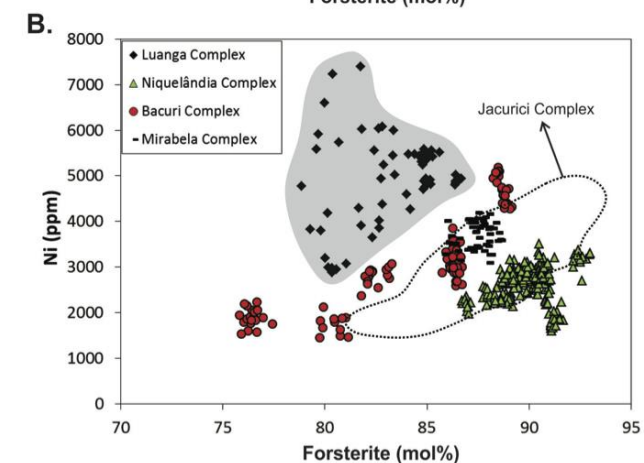
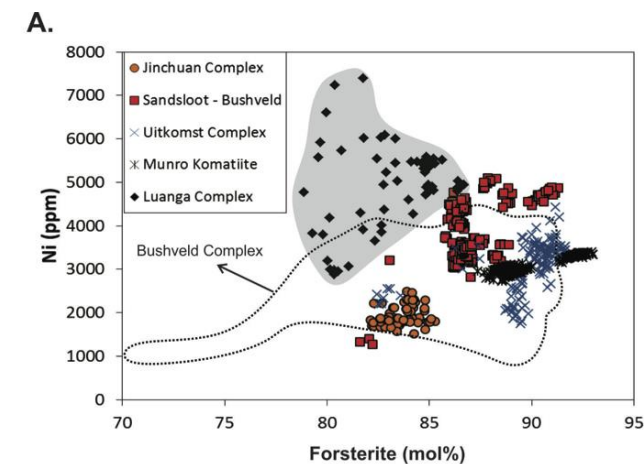
Luanga Complex

- High Ni contents in olivine of the Luanga Complex occur in distinctively PGE enriched (Pt+Pd > 1 ppm) zones, and they are not associated with BMS.

"Studies of the geological setting and composition of the recently discovered massive sulfides will be used to test the "dissolution upgrading model":



DDH22-LU047 – Massive Sulfide



Implications for the mineral system and exploration

- The massive sulfide ore (MASU) intercepted in DDH22-LU047 (11m at 4.24 g/t 3PGM+Au, 2.04% Ni, 1.23% Cu) had not been previously described at Luanga, thus providing new insights for mineral exploration and better understanding the PGE-Ni-Cu mineralization.
- Petrographic, mineralogical and chemical features of the massive sulfides are distinctively different from those described in the Main Sulfide Zone (MSZ) of the Luanga deposit. MASU does not result from remobilization and concentration of sulfides from the MSZ.
- Host rocks and the footwall sequence of the MASU consist of metasomatic rocks (amphibole-magnetite-biotite) similar to those commonly associated with IOCG system in Carajás. These rocks result from pervasive hydrothermal alteration of primary magmatic rocks from the layered intrusion. The mineralogy and chemical composition of the MASU are possibly modified during hydrothermal alteration.
- The Luanga Complex is the perfect setting to further investigate the possible connection between magmatic sulfide deposits and Ni-rich (e.g., Jaguar) and Au-PGE (e.g., Serra Pelada) hydrothermal deposits in Carajás.

Thank you



Luanga 2022