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Magma and Metals: Applying mineralogy to solve petrological and mining challenges



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Typical “normal” Merensky Reef
at Townlands shaft Rustenburg
(Naldrett et al., 2015)

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- The petrogenesis of mafic/ultramafic layered intrusions and their mineralization remains a huge challenge
- Genetic models not always consistent with field observations
- Scarcity of studies that link macroscopic and microscopic observations
- The mismatch affects:
 - local geological confidence and geological modeling,
 - later on in the mine value chain during mineral processing

Examples from the Merensky Reef, Bushveld Complex

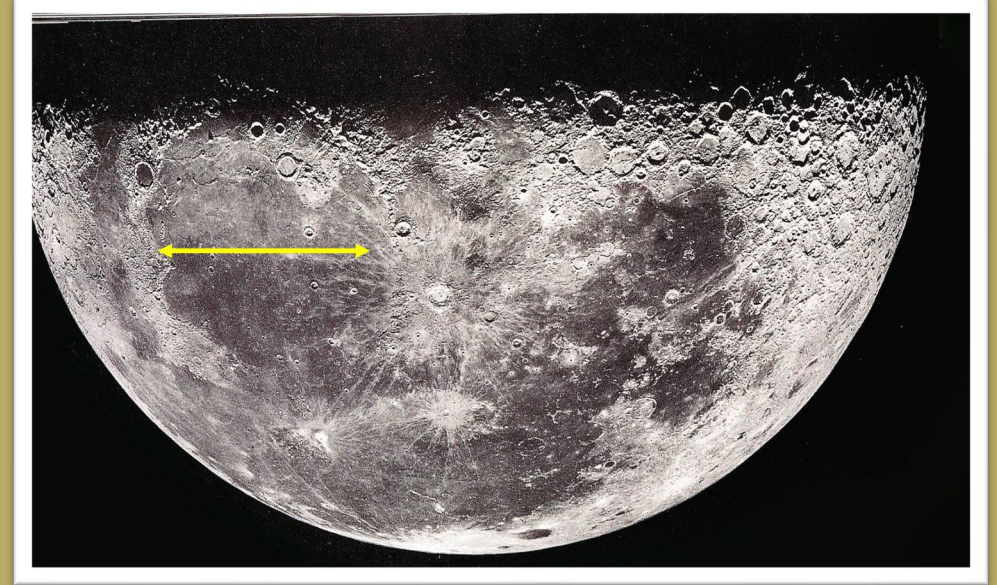
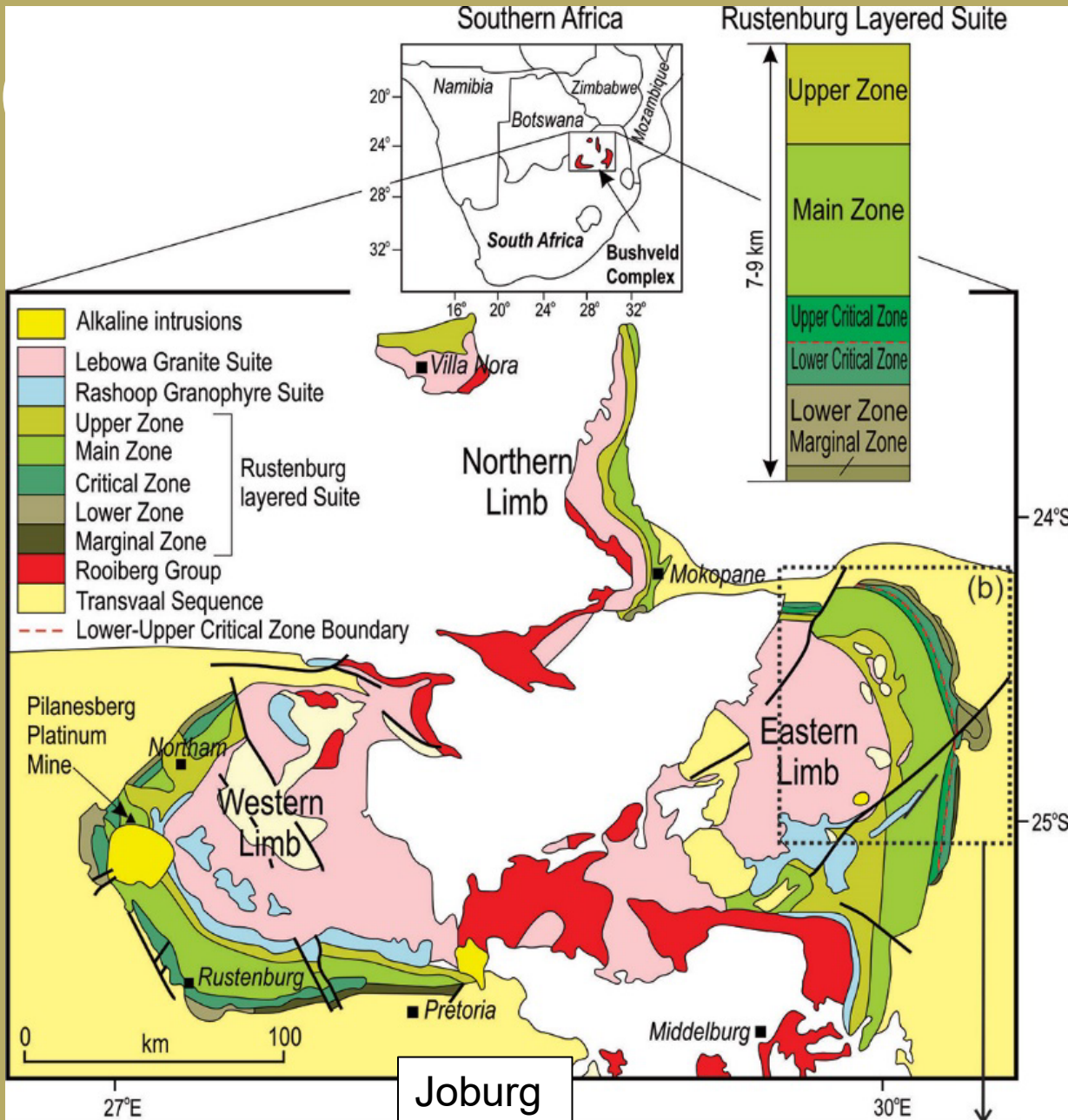


The Merensky Reef (MR)



- One of the world's largest repositories of platinum-group elements (PGE)
- Discovered in 1924 by Hans Merensky and mined since 1926
- Shallow dipping tabular layer with 5 to 8 g/t PGE (Pt,Pd,Rh) +Au, with Ni and Cu benefits
- The reef presents a challenge to understanding how igneous processes lead to the extreme concentration of metals in a magmatic ore deposit
- The origin is still highly debated

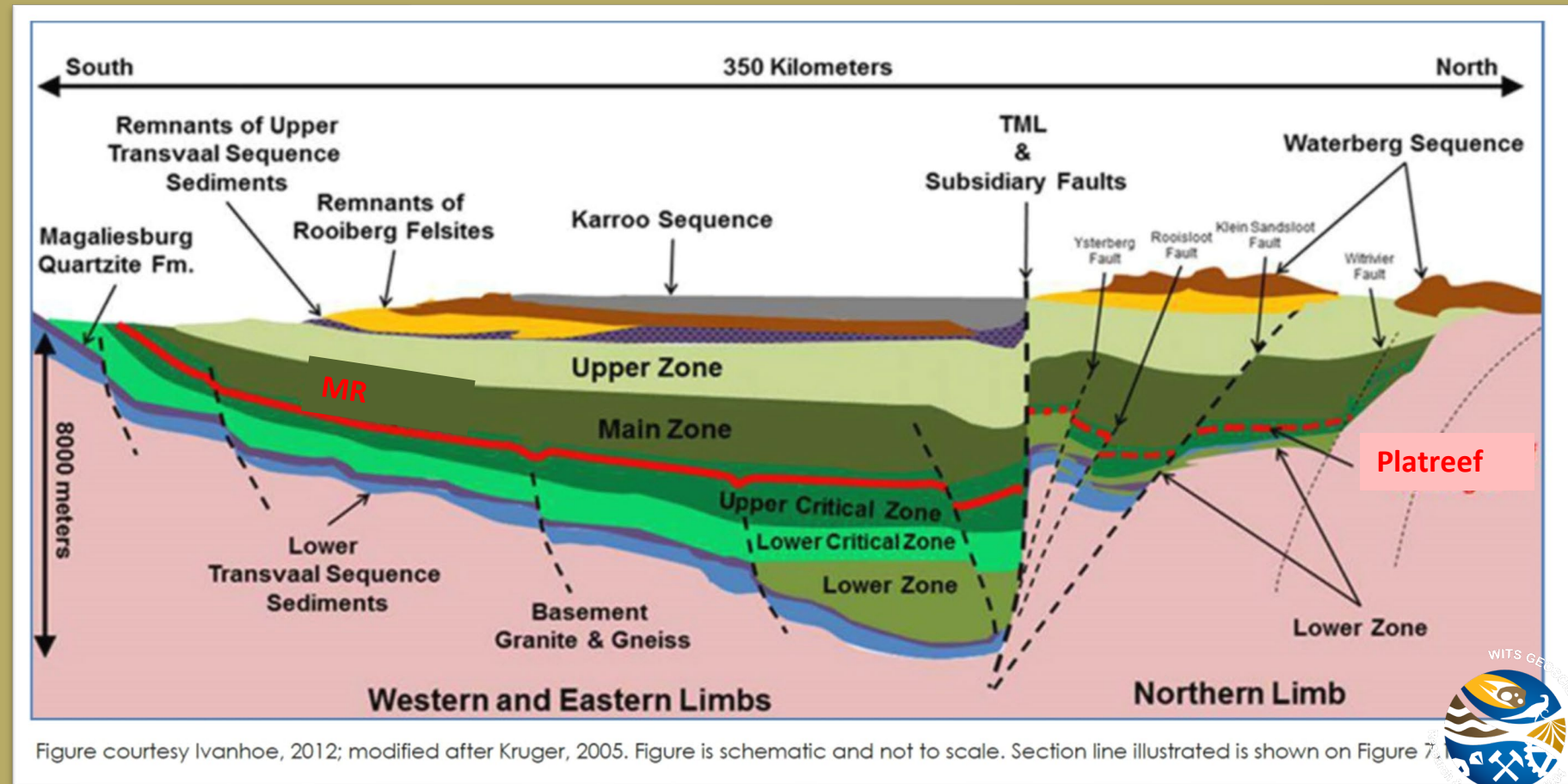
The Bushveld Complex



- largest layered mafic-ultramafic intrusive suite on Earth, area of ca. 95,000 km²
- intruded between 2060 and 2054 Ma into an Archean basement
- world's largest reserves of Cr and PGE's
- Subdivided in Lobes/Limbs as partially exposed

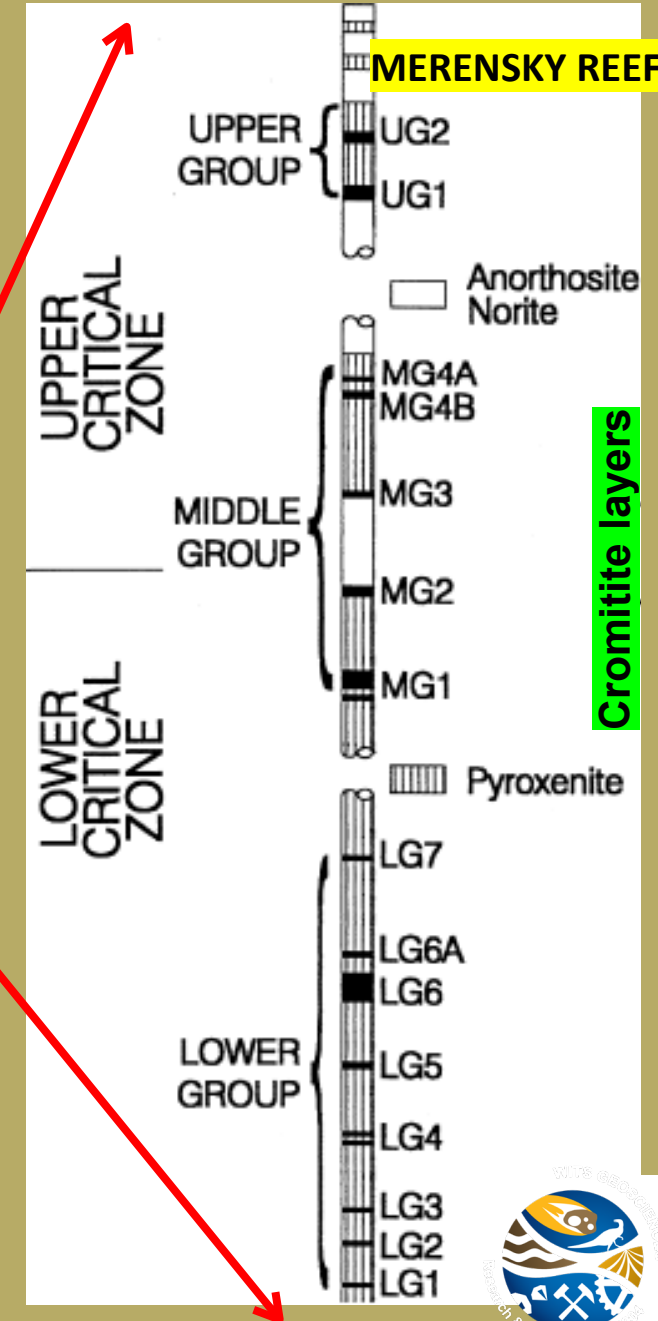
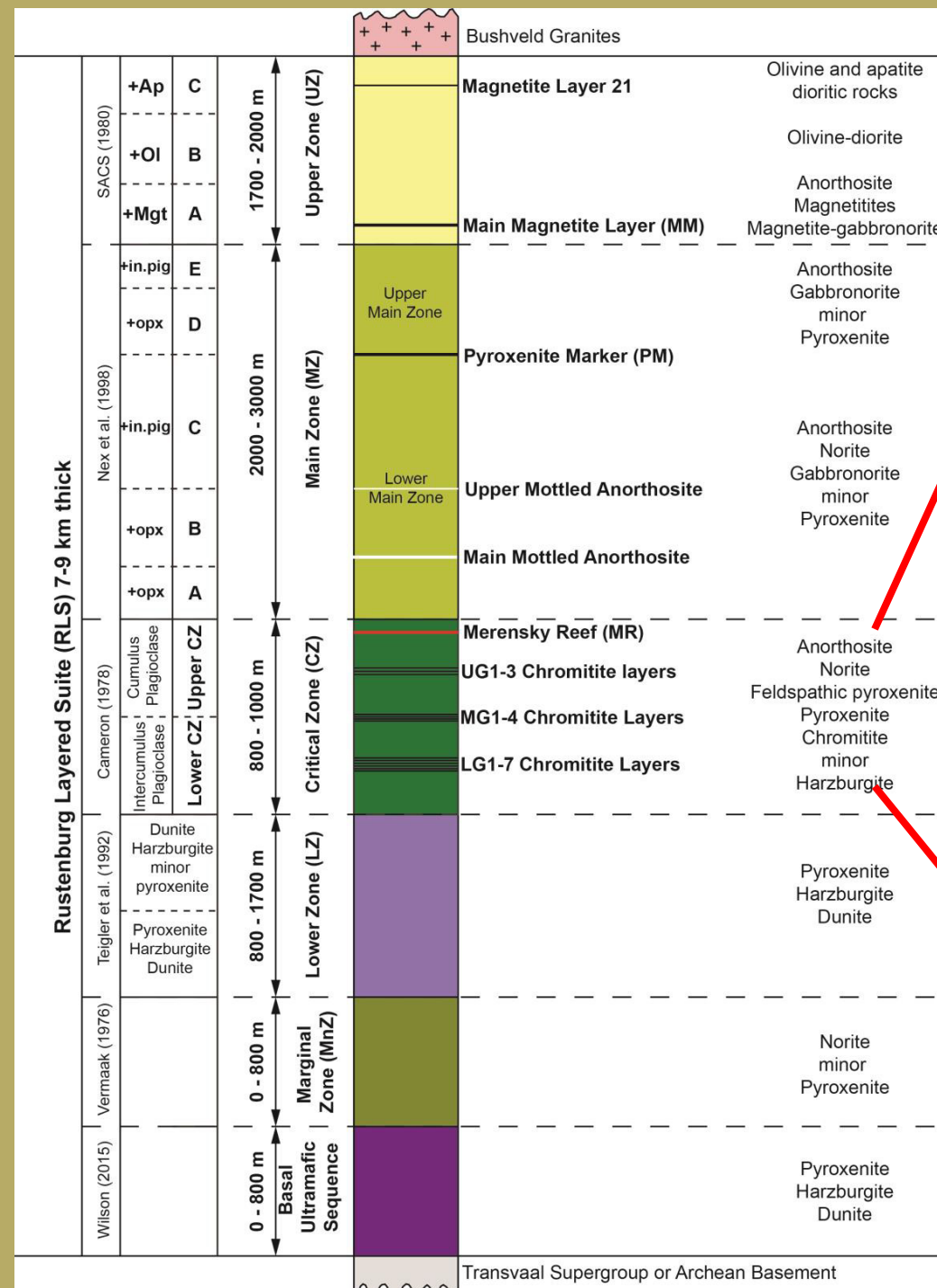
The Bushveld Complex and the Rustenburg Layered Suite

- Lobes/Limbs are connected in saucer-shaped and sill-like, dipping inward 9-27°
- stratiform reefs that can be traced along strike for several 100 kms in the different limbs
- The ultramafic/mafic rocks succession forms the 7 km Rustenburg layered Suite, which is overlaid by about 3 km granite suite (Rashoop/Lebowa suites, which hosts tin mineralization)



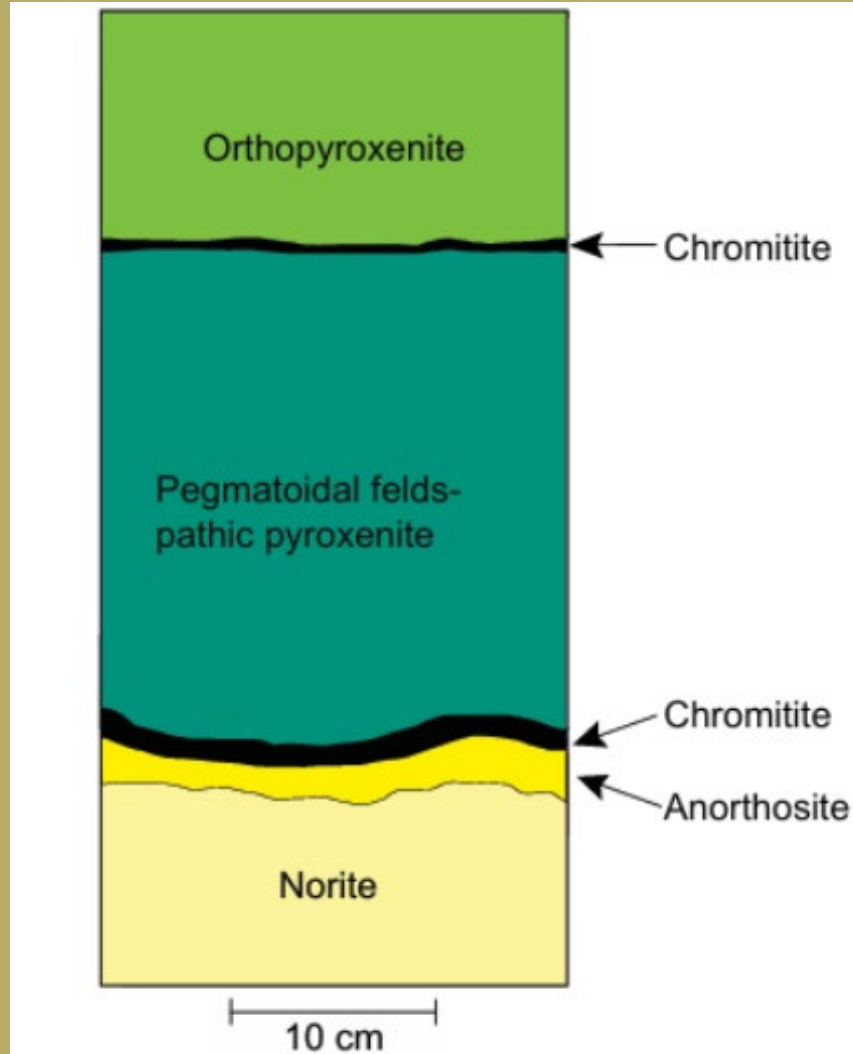
The Rustenburg Layered Suite, subdivided in

- UPPER ZONE
- MAIN ZONE
- CRITICAL ZONE
- LOWER ZONE

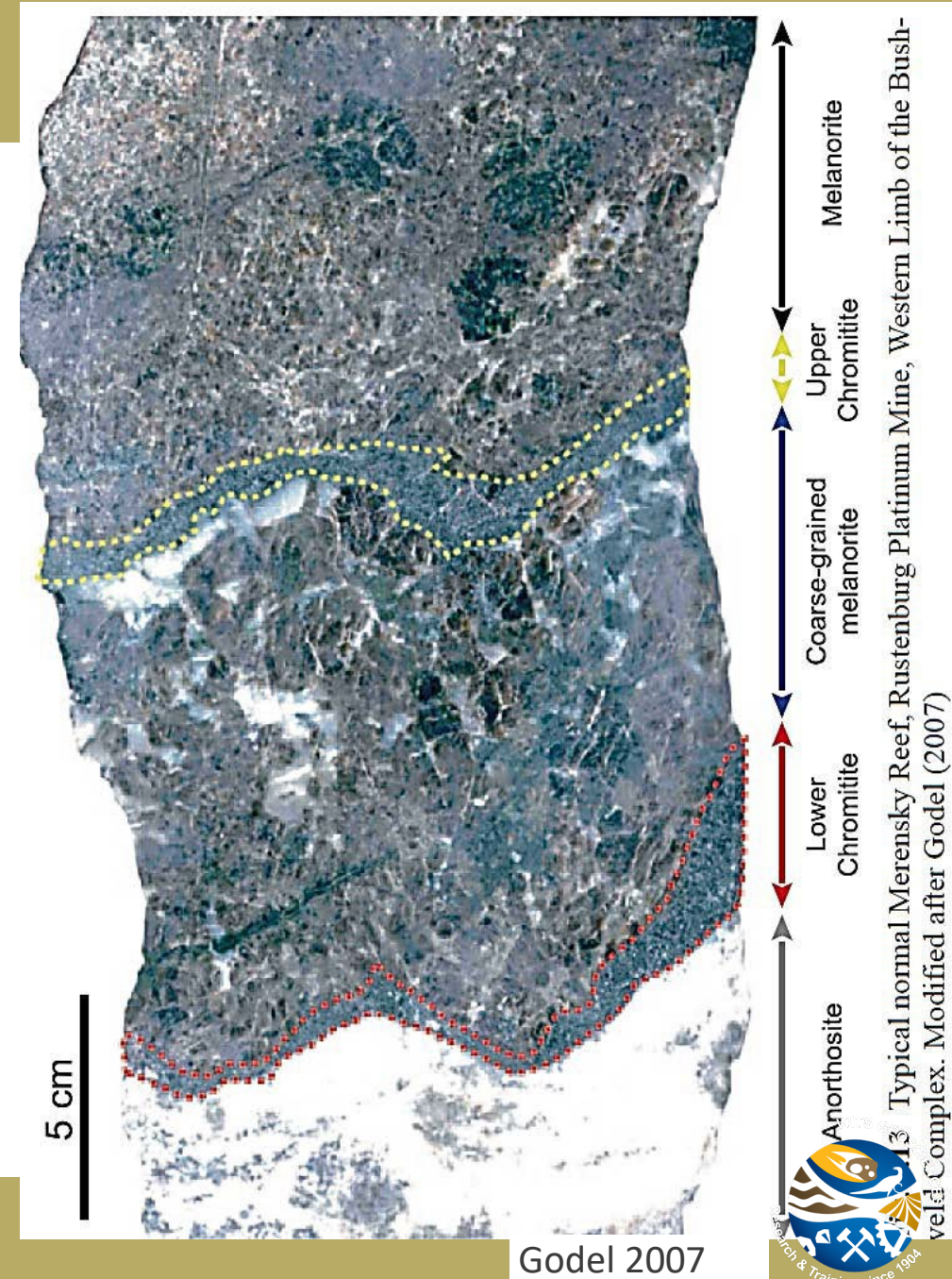


Merensky reef typical stratigraphy

- typically a “pegmatoidal” feldspathic pyroxenite, bounded by narrow (± 1 cm) top and bottom chromitite stringers
- Variable thickness
- footwall lithology typically noritic or anorthositic
- Often not concordant to magmatic layering

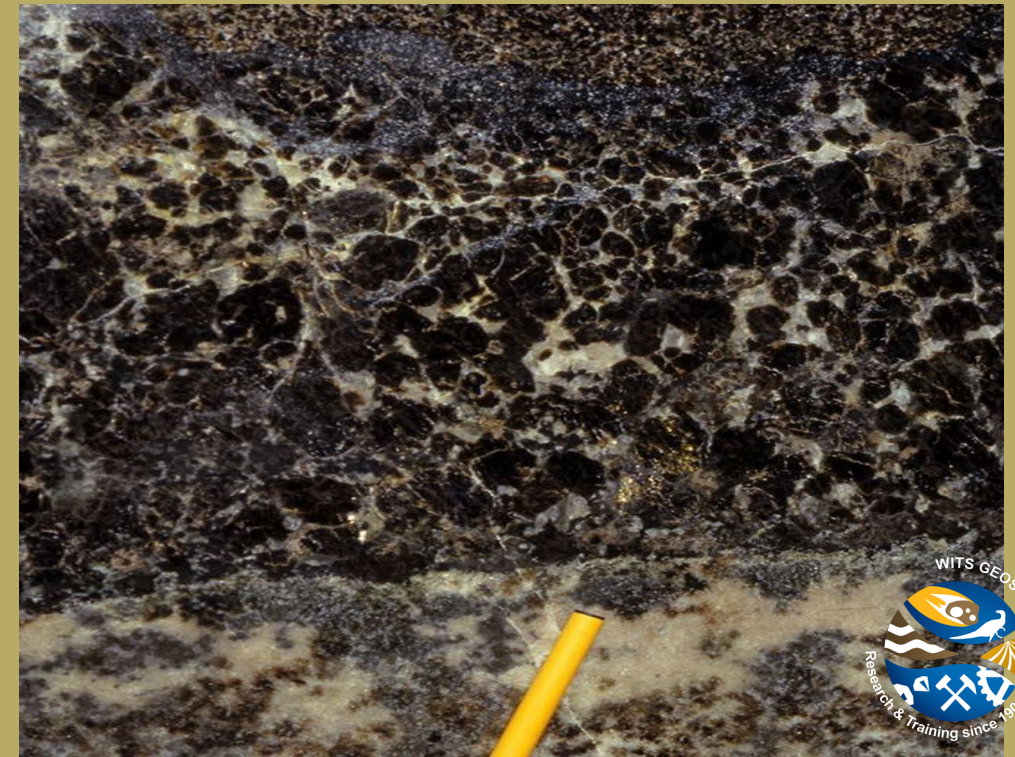


Mathez and Kinzler, 2017



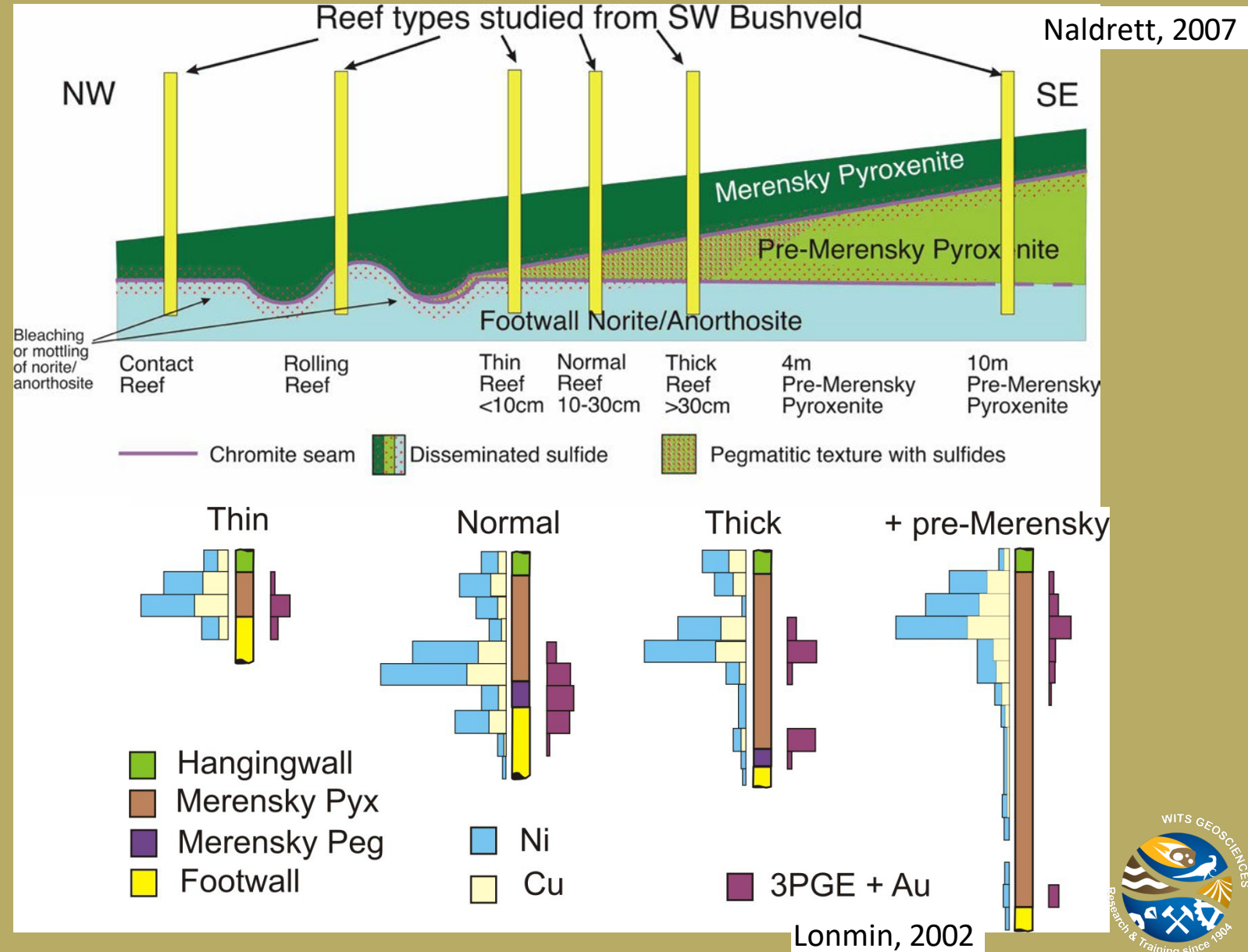
Godel 2007

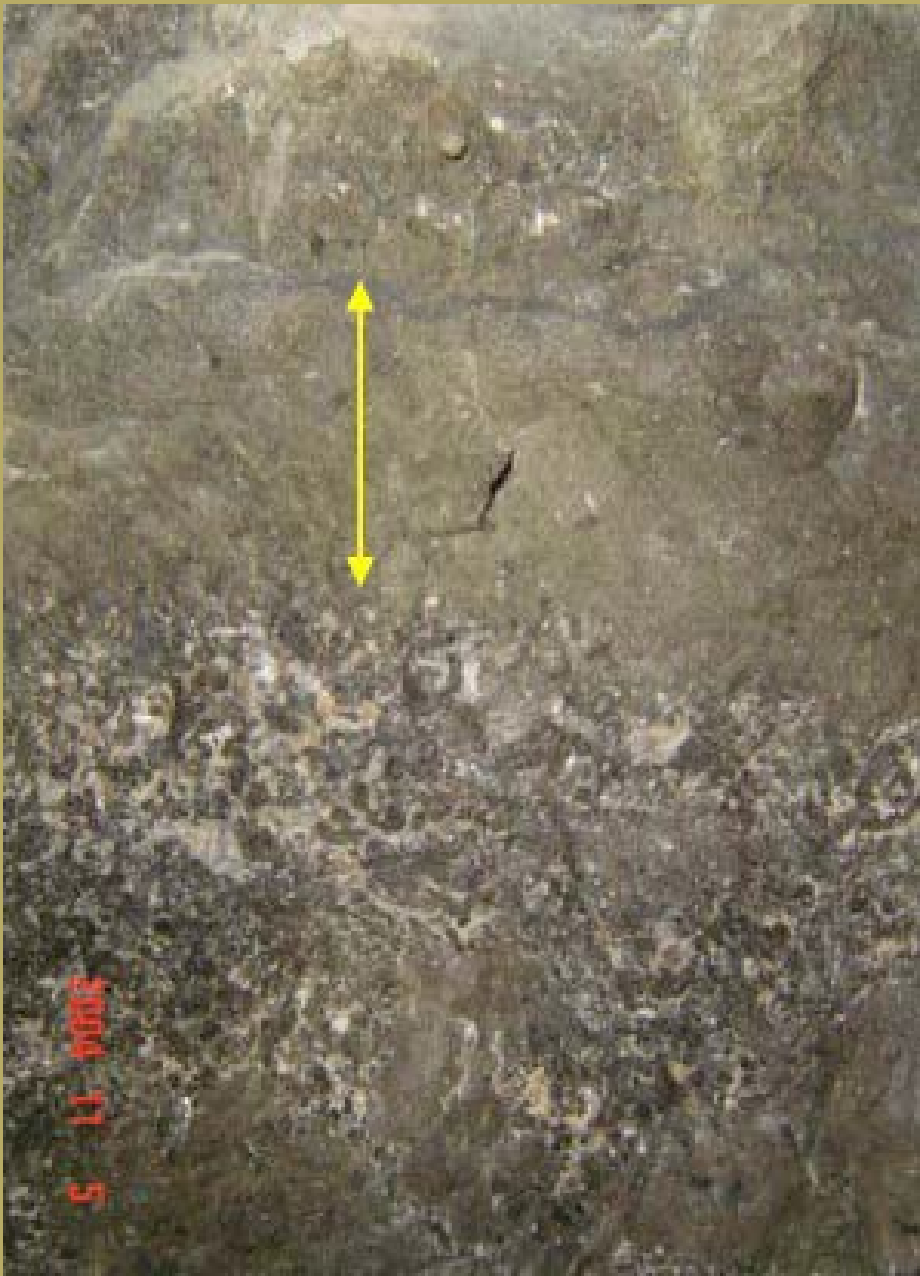
- Feldspathic Pyroxenite = consists of 70-90% orthocumulate (framework of cumulus) bronzite (opx) crystals, typically 10–20 mm in diameter, <30% interstitial plagioclase, large accessory cpx, phlogopite mica $\pm$ olivine
- Reef may be of pyroxenite type or pegmatoid type, characterized by very large and heterogeneous orthopyroxene crystals
- large variations in reef thickness, reef composition, and the position of the mineralization.
- Mines define different facies, with variable thickness of the reef and different footwall lithologies



Merensky Reef - variation in type and grade distribution – Western Limb

- The grades generally increase with an increase in the pegmatoidal texture
- highest grade associated with basal and top chromitite stringers (**top-loaded reef**)
- Mineralisation not always visible with naked eye, and not always associated with sulphides





Photos Prof Kinnaird



- Normal Merensky Reef from Atok in the Eastern Limb of Bushveld Complex
- The arrows indicate the reef width, scale = 25cm
- Note the medium-crystalline texture of the reef layer and the pegmatoidal texture of its immediate footwall

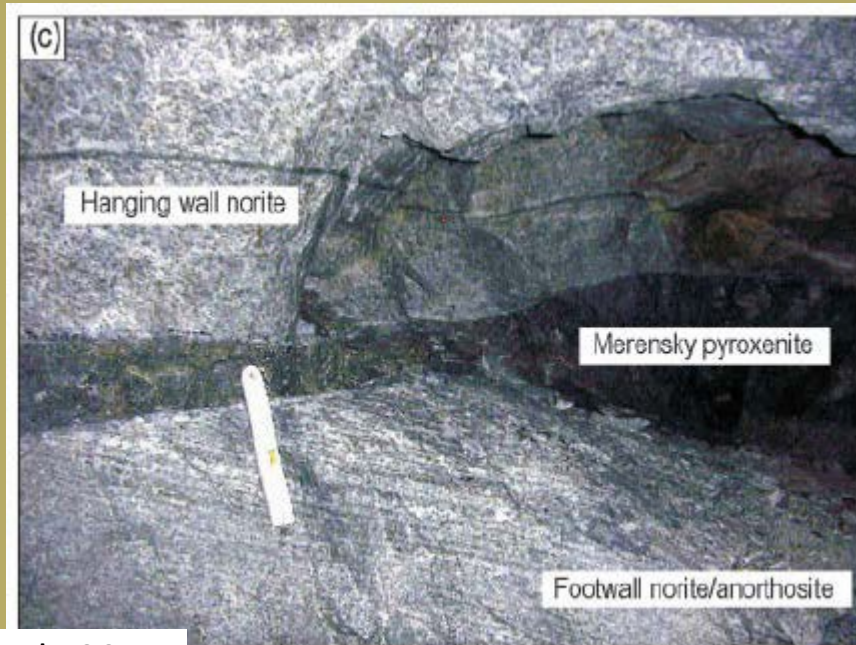
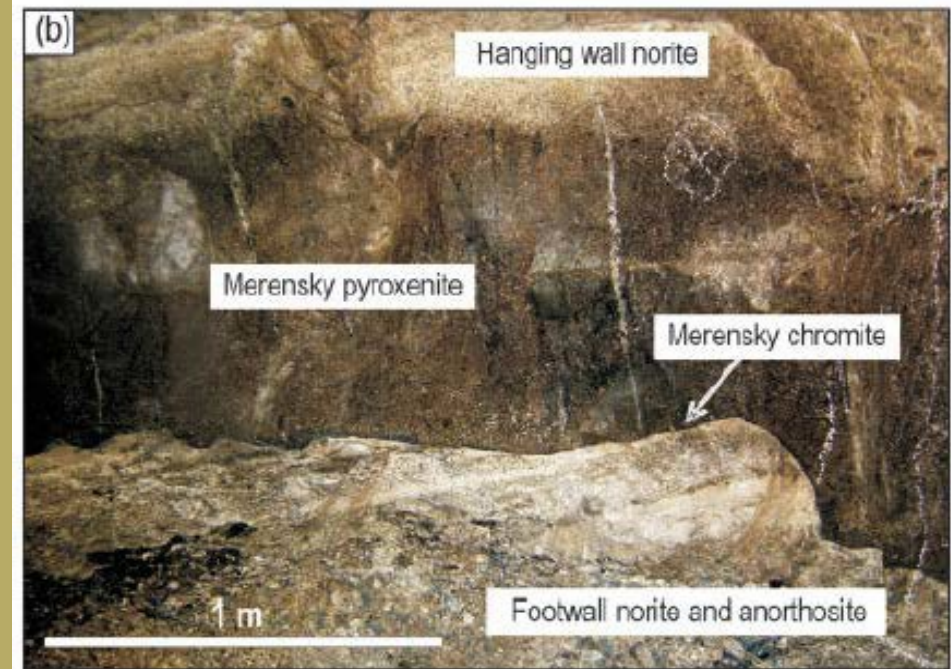
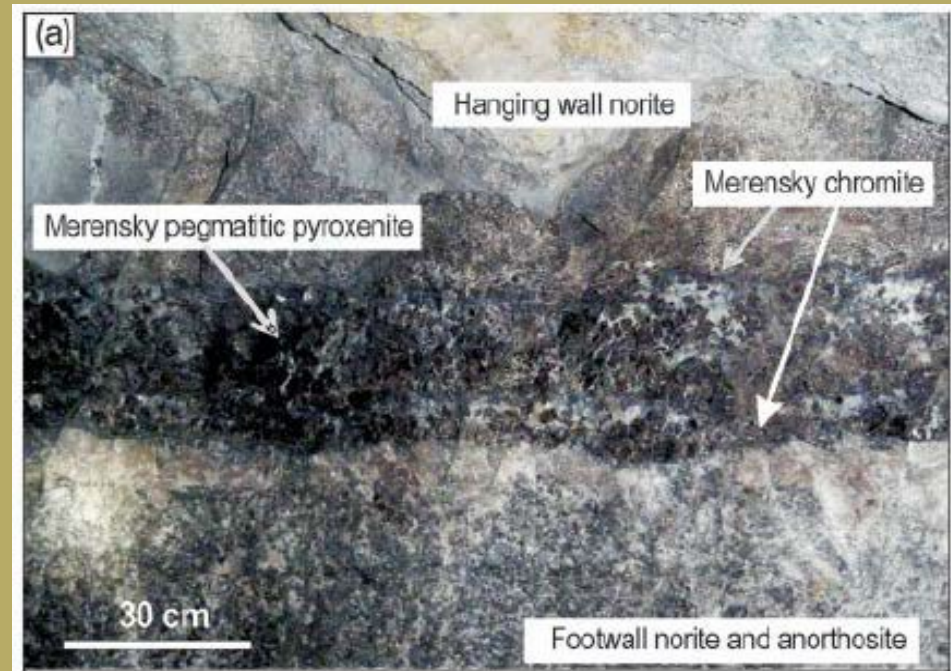


Photos Prof Kinnaird

- Basal contact of Normal-type Merensky Reef at Northam, Western Limb
- Pegmatoidal texture of the reef
- Ondulating basal chromite stringer
- Footwall represented by anorthosite

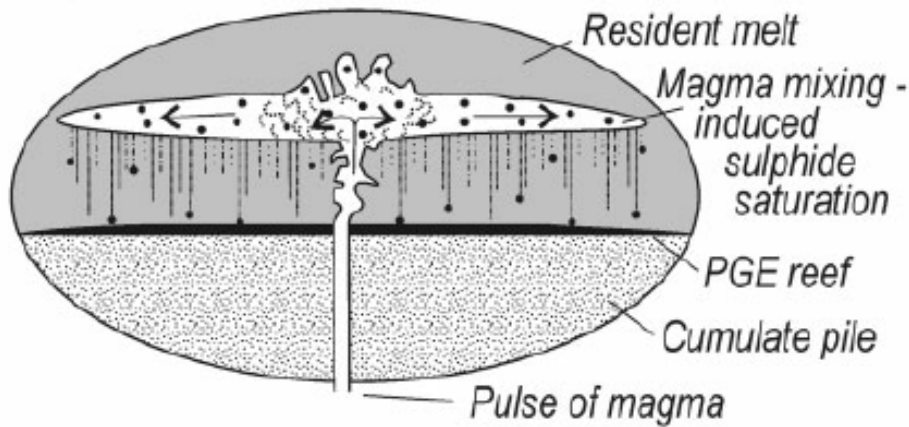


- a) Normal MR pegmatitic orthopyroxenite with lower and upper chromitite seams (Thembelani Mine) with up to 4–6 chromitite seams
- b) Only the bottom chromitite seam at Eastern Platinum Mine. Reef discordant to layering in the footwall norite and anorthosite.
- c) Brakspruit Shaft, Rustenburg Platinum Mine, MR drapes over the side of a mound and truncates the layering in the underlying norite and anorthosite.

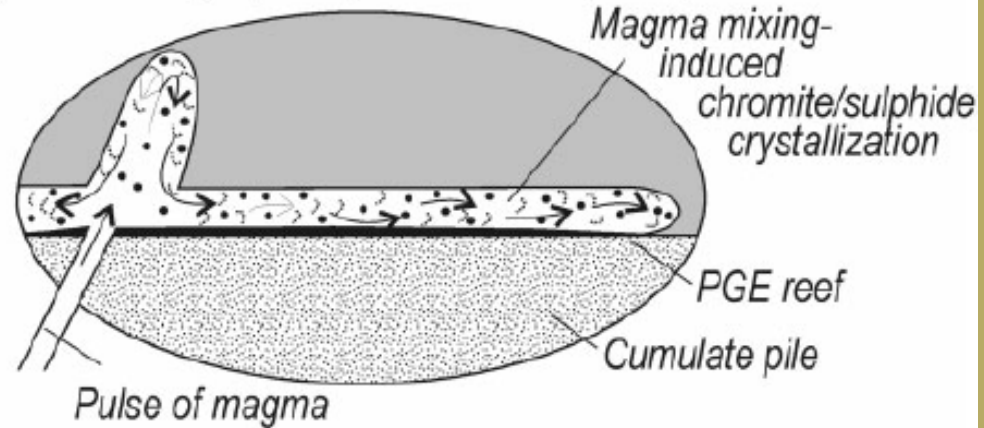


Many petrological models proposed, none can explain all local variations

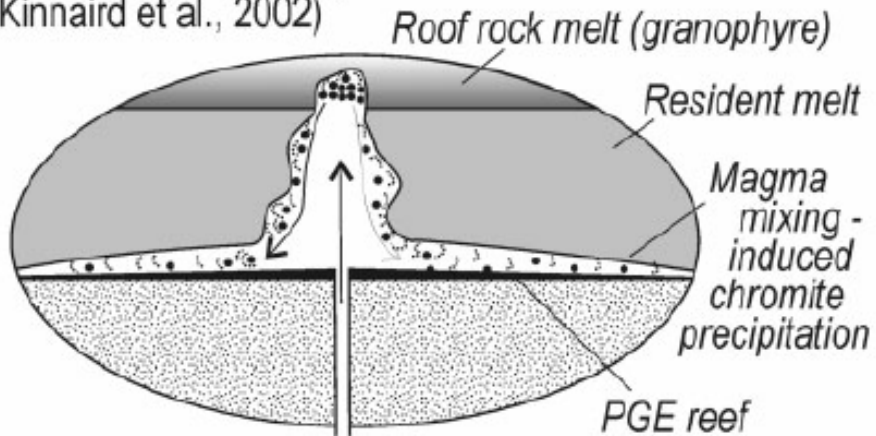
(a) Magma mixing
(Campbell et al., 1983; Naldrett et al., 1987)



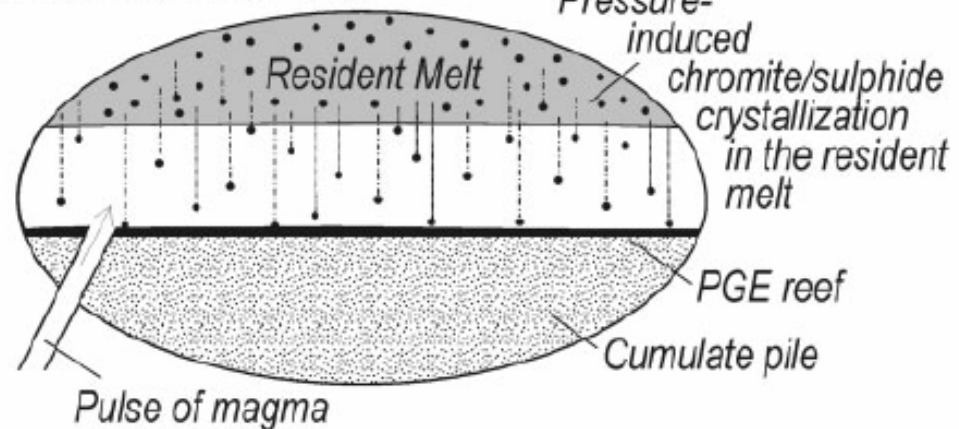
(b) Lateral mixing model
(Scoons & Teigler, 1994; Naldrett et al., 2011)



(c) Roof magma mixing
(Kinnaird et al., 2002)

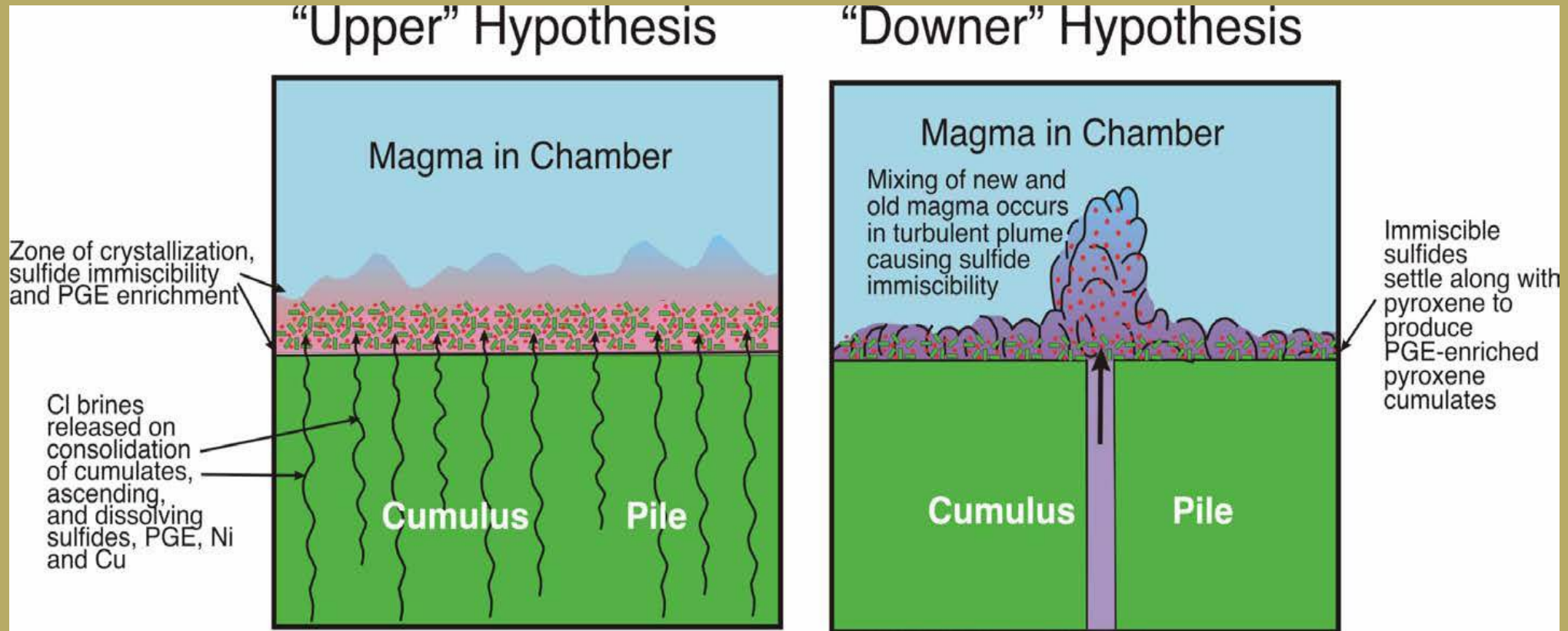


(d) Pressure-induced crystallization of sulphide/chromite
(Cawthorn, 2005; 2011)



Two (or more) magmas were involved in the formation of the MR

Two competing hypotheses to explain the concentration of PGE in thin reefs



Introduction of PGE by interstitial fluids migrating upward from the underlying cumulates

Ballhaus et al., 1988; Mathez, 1995; Mathez et al., 1997;
Boudreau & McCallum, 1992; Boudreau, 1995, 2008;
Boudreau & Meurer, 1999

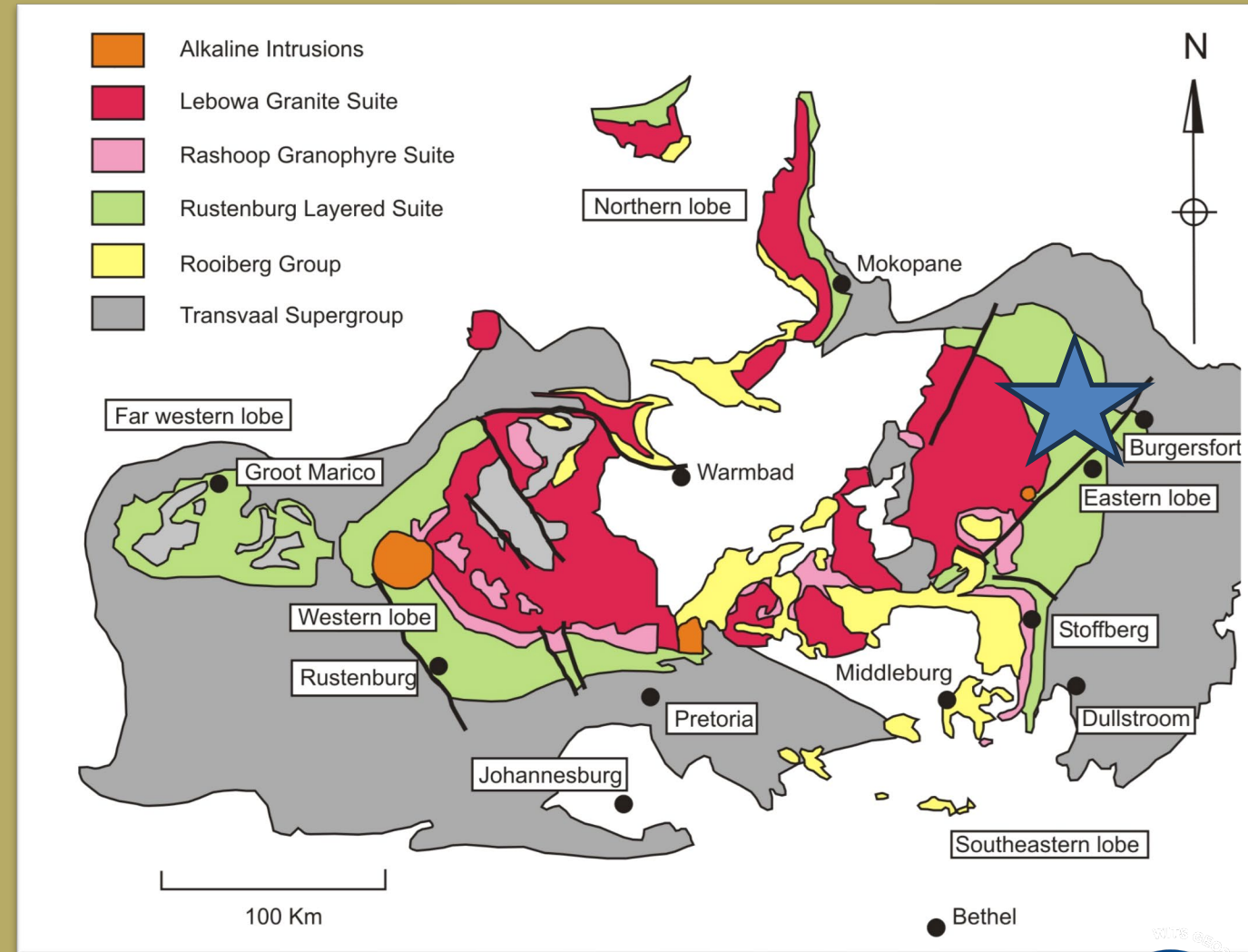
Settling of dense immiscible sulphide melt from the overlying magma

Campbell et al., 1983; Naldrett et al., 1987;
Naldrett, 1989; Barnes & Maier, 2002; Naldrett et al., 2009, 2011, 2012

This project aims to document a **pothole structure** of the Merensky Reef at **Modikwa Mine**, Eastern Limb

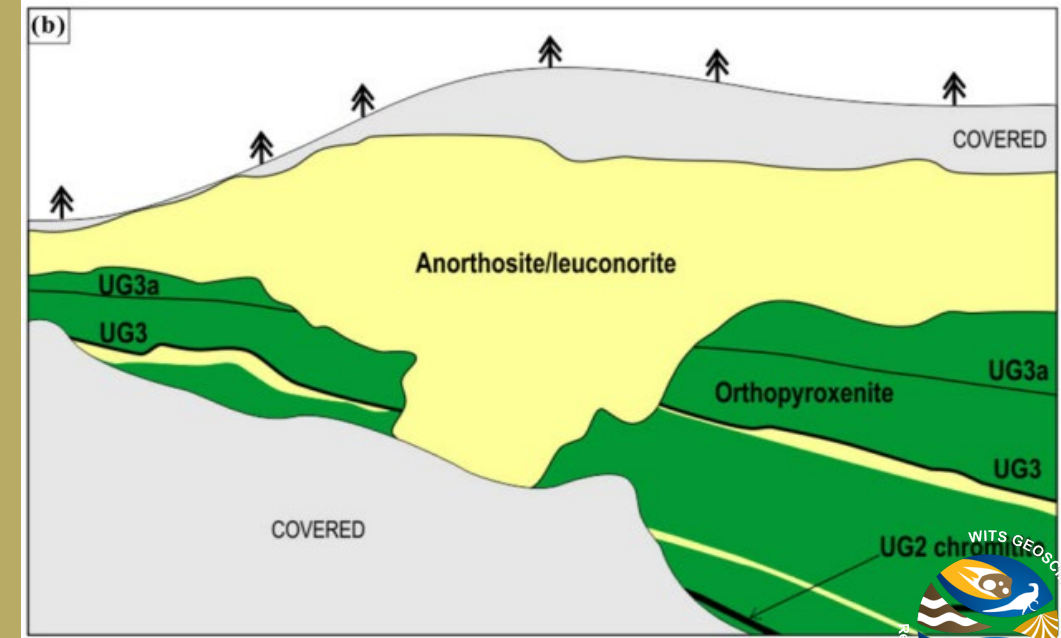
Methodology:

- **Underground mapping:** normal reef and pothole facies and samples collection
- Detailed **petrography** of samples representing contacts between rock types to understand the magmatic relationship between them
- **In-situ analyses** of major mineral phases and trace elements using **Micro-XRF** on hand specimens and **TIMA** on thin sections



What are **pothole structures** in the Bushveld Complex?

- Disturbance in the magmatic layered sequence ascribed to erosion of the footwall by hotter magma
- Formation related to magma chamber replenishment and magma mixing influence reef formation (Smith et al., 2025) and Magmatic erosion and chemical dissolution of cumulates (Latypov et al., 2022)
- Problematic for mining



Latypov et al., 2022



Underground mapping and sampling at Modikwa Mine



Merensky Reef pothole structure at Modikwa Mine

Mottled Anorthosite
truncating MR pyroxenite

Merensky Reef
Feldspathic
Pyroxenite



Sulphides



Chromitite stringer

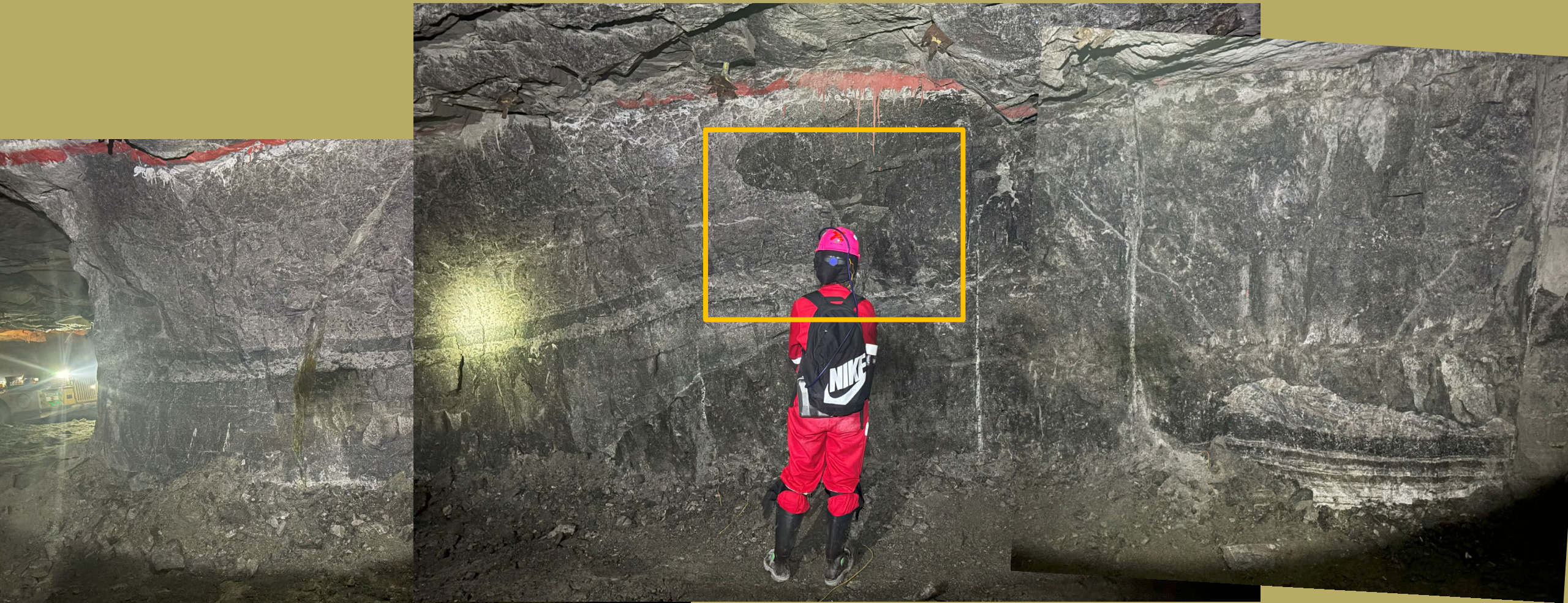
Late vertical
pegmatite dykes

Footwall with
magmatic layering
truncated by MR

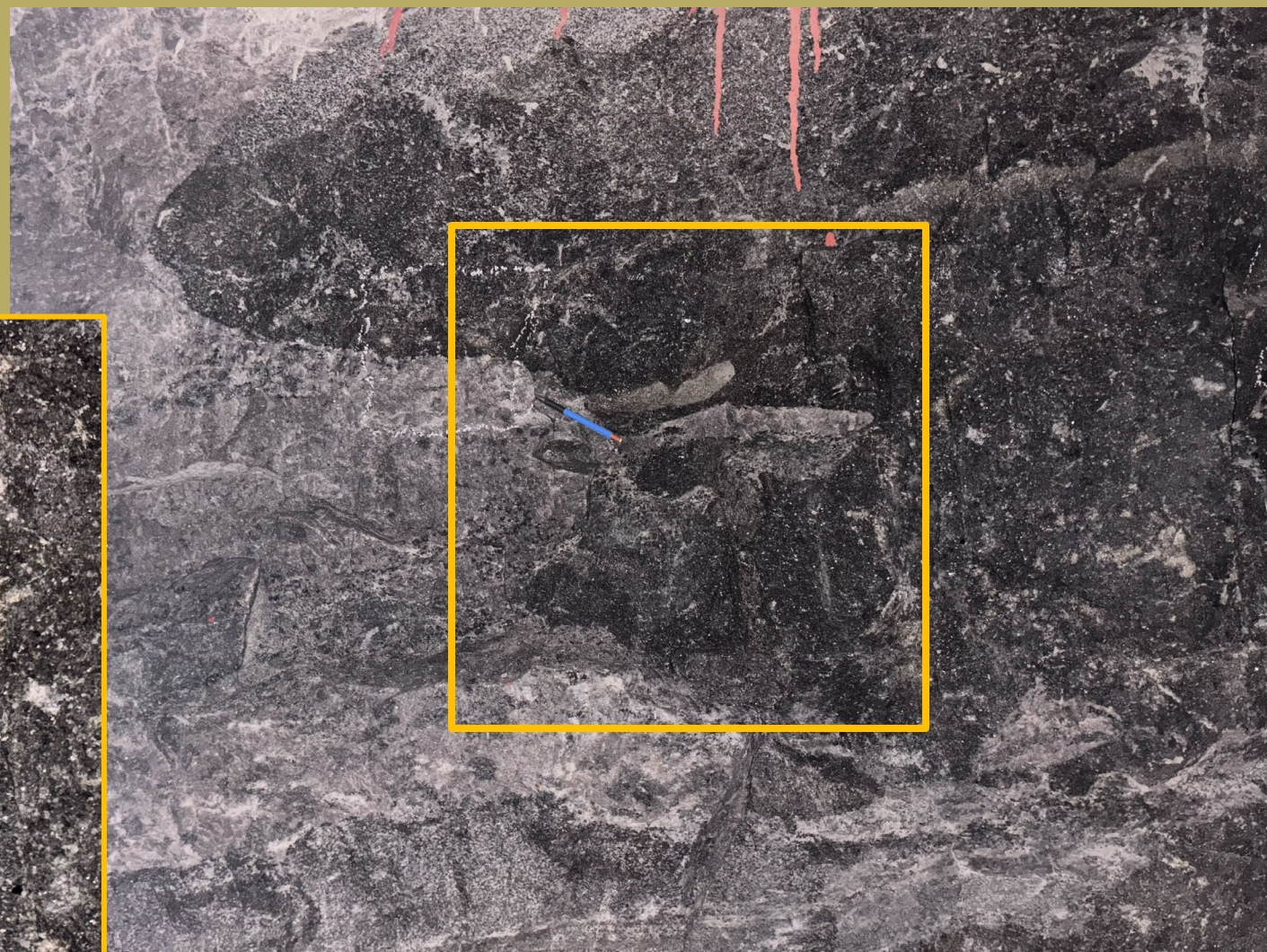
Underground sampling



Contact between Merensky felspathic pyroxenite and mottled anorthosite

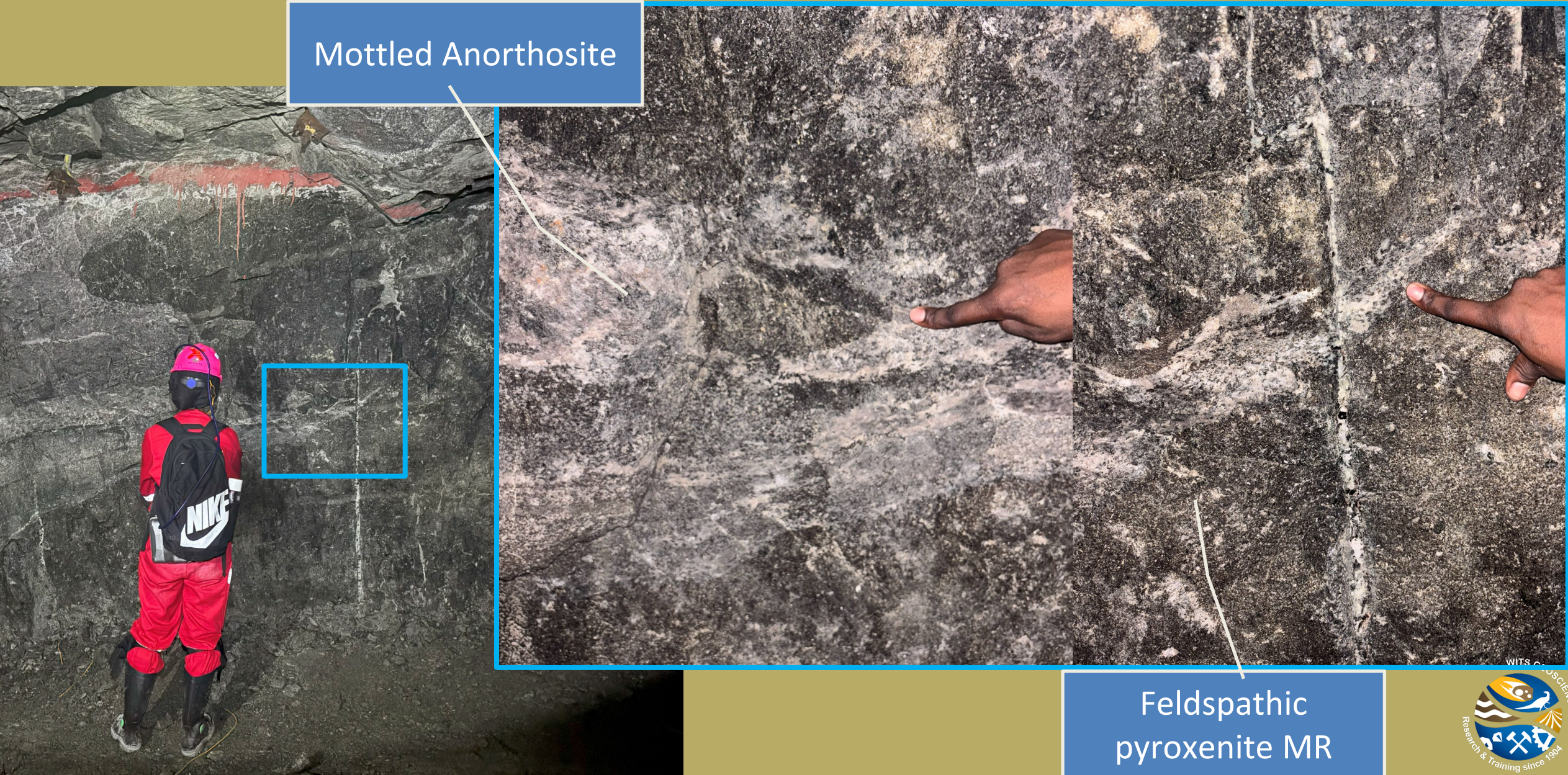


Contact between Merensky felspathic pyroxenite and mottled anorthosite

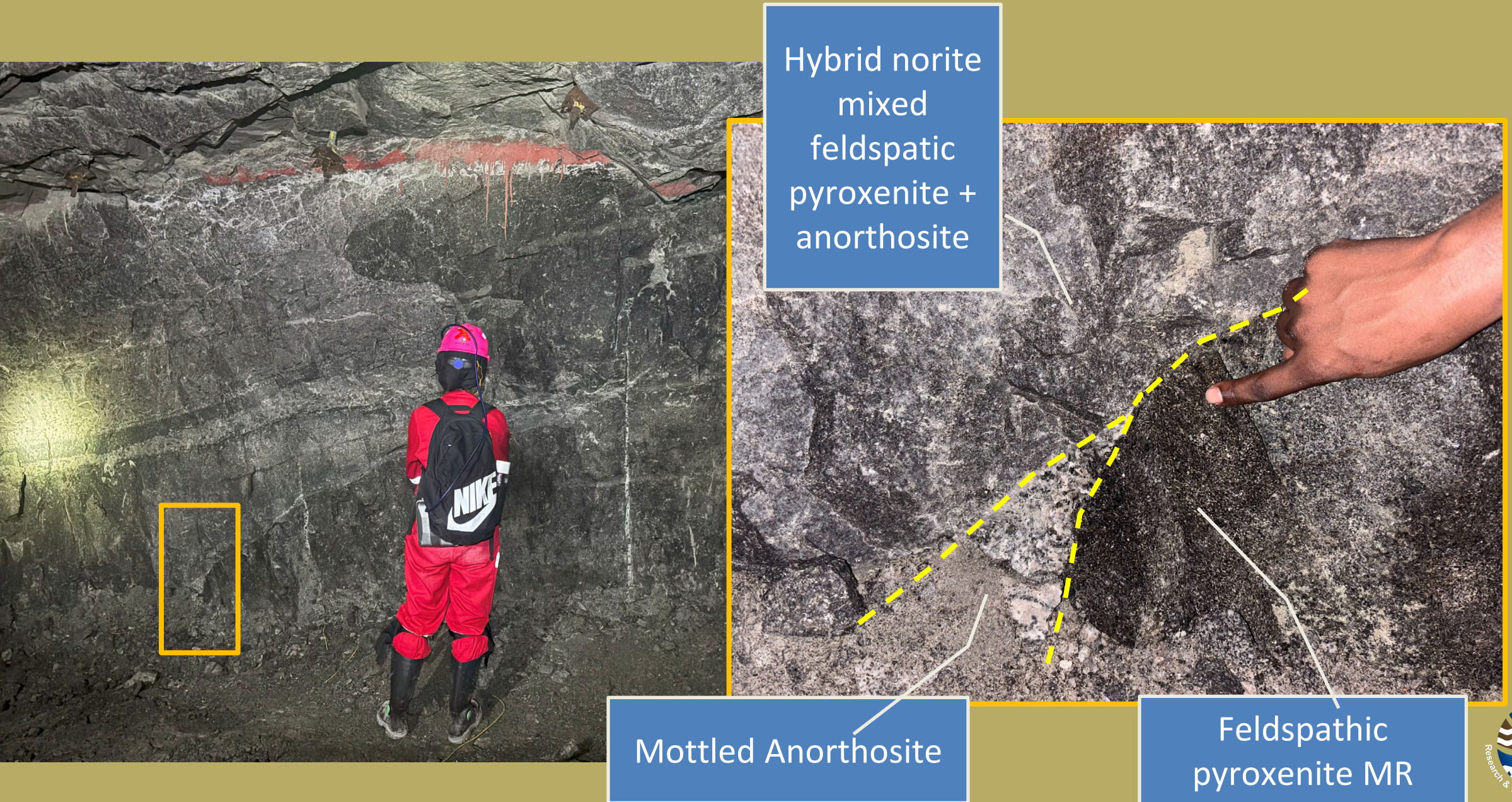


- Anorthosite interfingering into the Merensky feldspathic pyroxenite
- Anorthosite show internal magmatic layering

Contact between Merensky felspathic pyroxenite and mottled anorthosite



Contact between Merensky felspathic pyroxenite and mottled anorthosite



Magmatic layering within mottled anorthosite



Mottled Anorthosite

Feldspatic
pyroxenite
Sharp top
contact,
rolling
bottom
contact

Mottled
Anorthosite

Hybrid norite

Chromitite stringer with
drooping pyroxene/sulfides
aggregates

Sharp contacts between magmatic rocks

Pyroxene
oikocrysts/mottles
subparallel to layering

Chromitite stringer with
drooping pyroxene/sulfides
aggregates

 Sulphides



Magmatic layering within mottled anorthosite



Gravitational settling (?)
subparallel pyroxene oikicrysts
(mottles) in anorthosite



Magmatic layering within mottled anorthosite



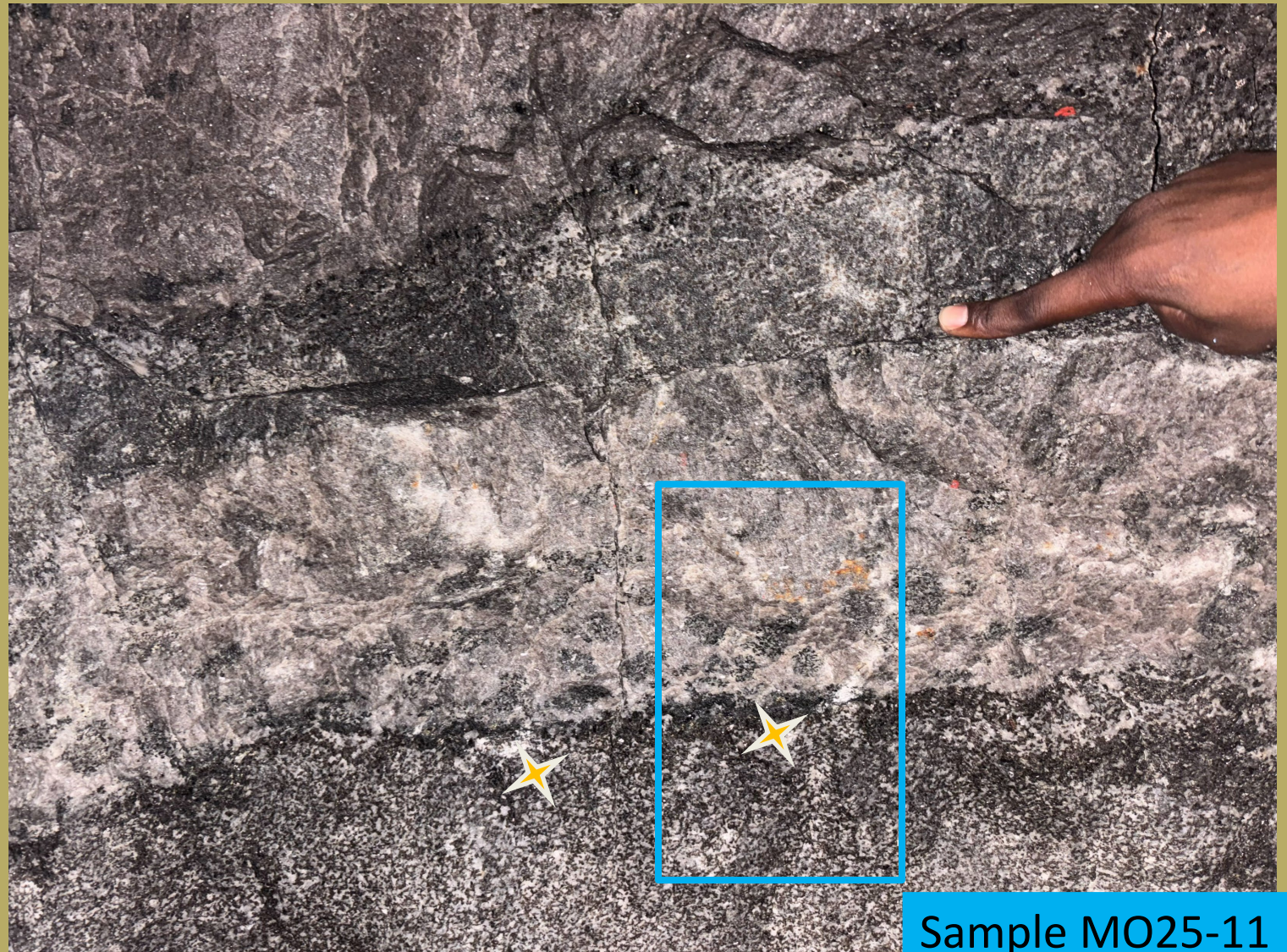
Details magmatic layering within mottled anorthosite



Diffuse upper contact

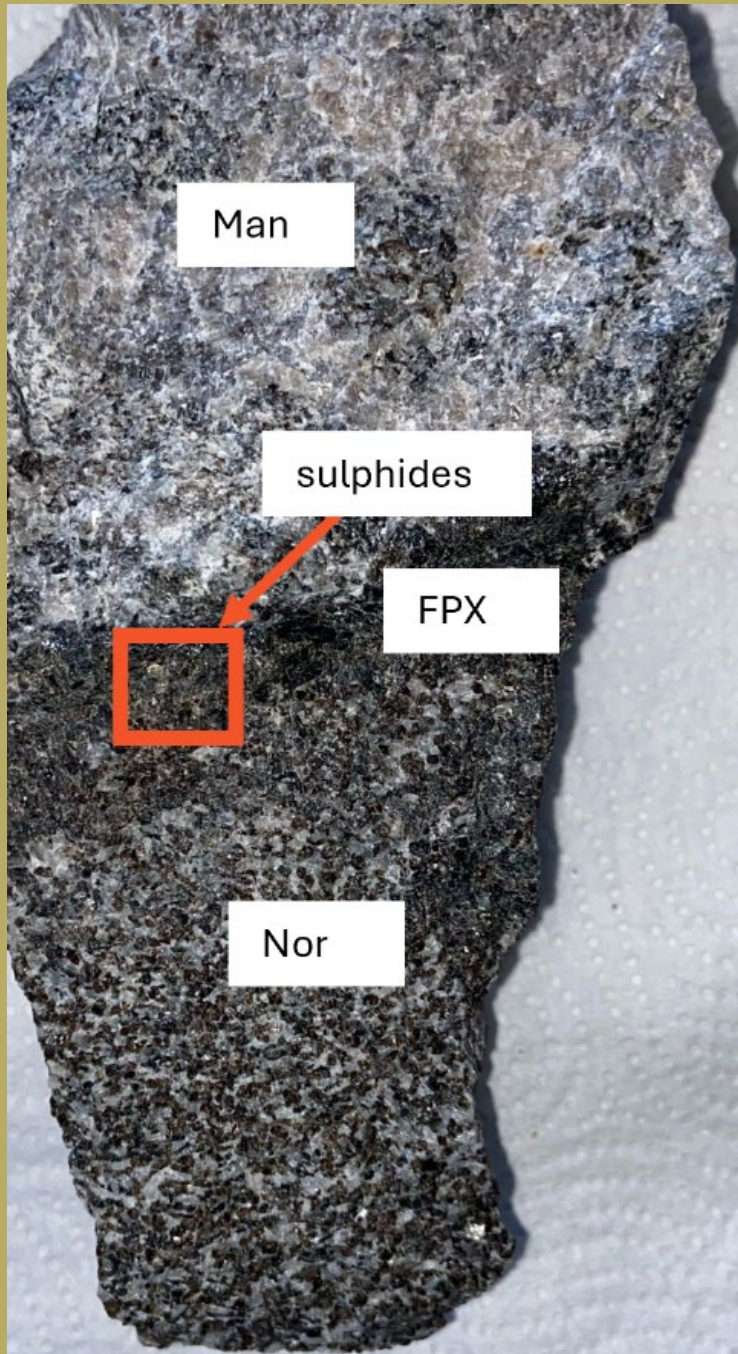
The magmatic layering within the anorthosite is characterised by:

- sharp and diffuse contacts
- Alternation of different magmatic rocks with variable grain sizes
- Sulphides associated with chromite stringers and reaction zone between pyroxenite/anorthosite

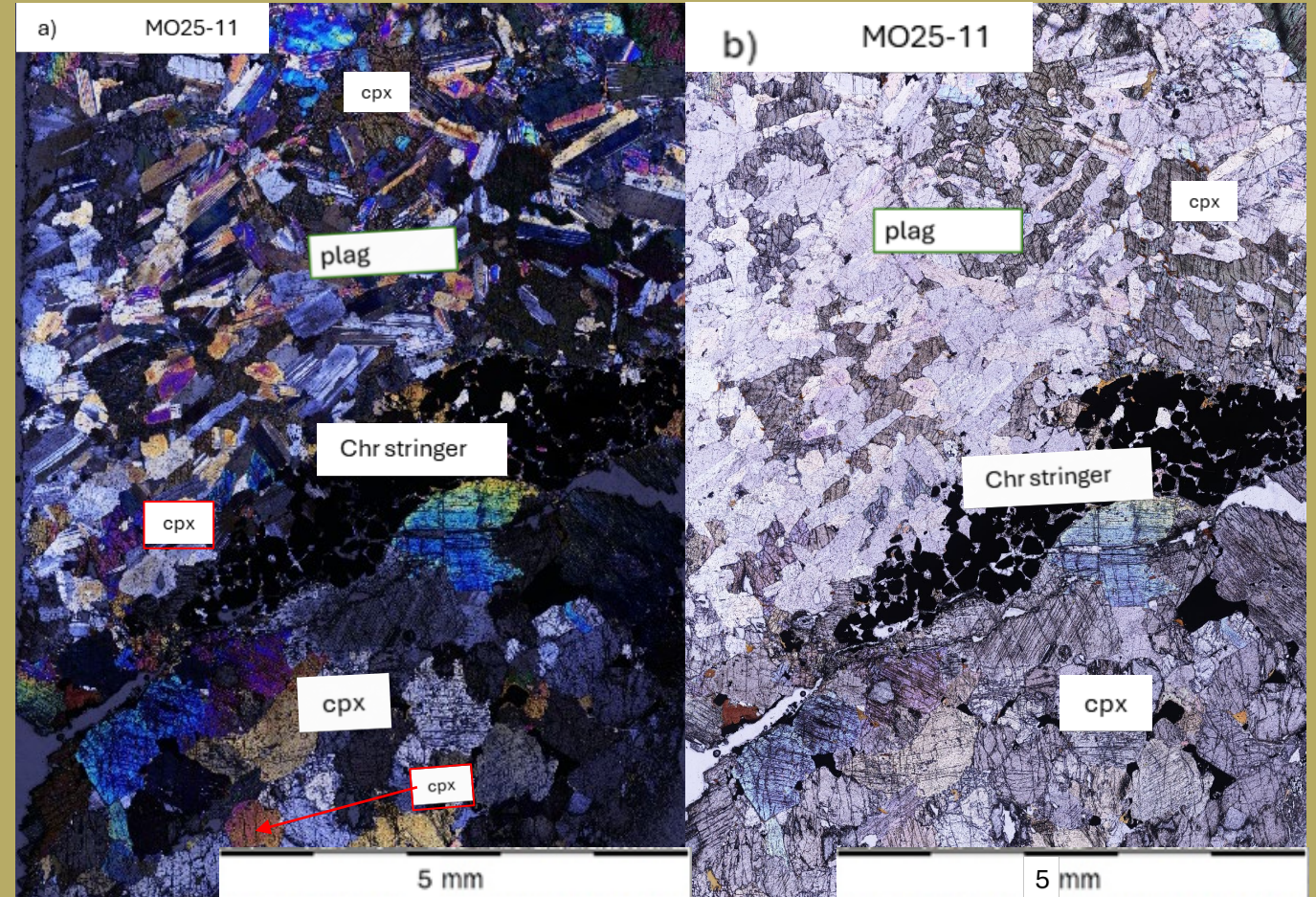


Sample MO25-11

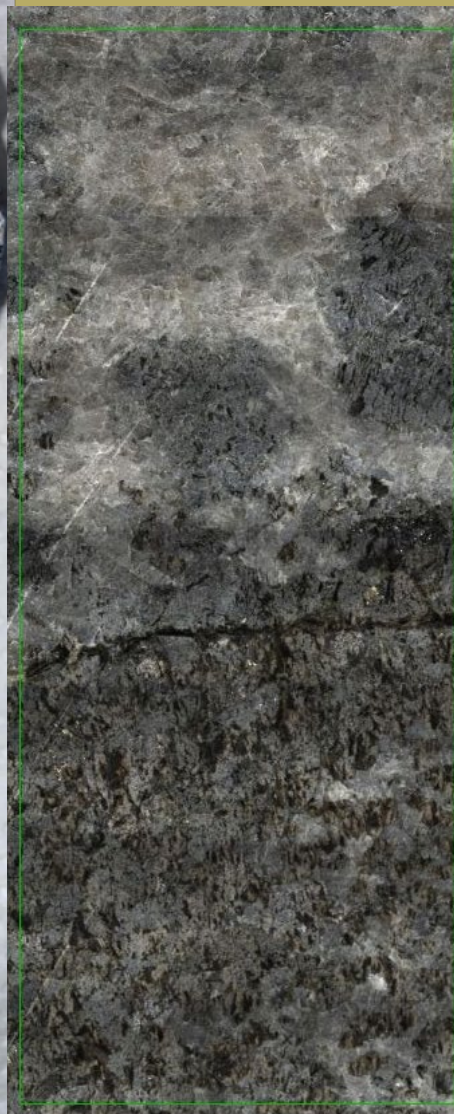
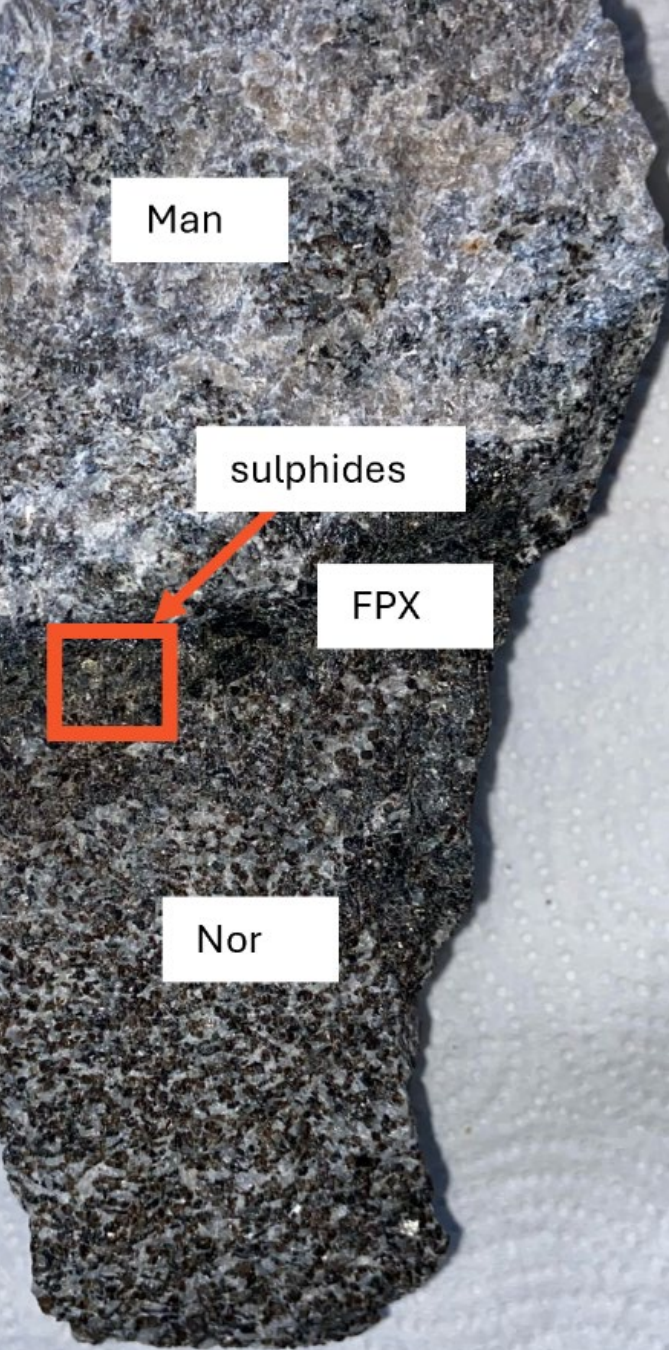
Sample MO25-11



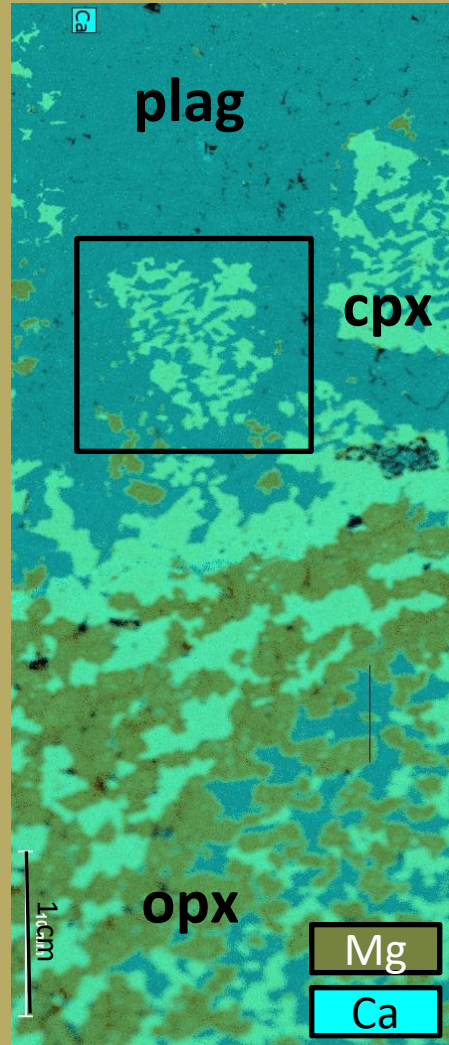
Up



- Four lithologies: Mottled anorthosite (Man), feldspathic pyroxenite (FPX), chromitite stringer and hybrid melanonorite (Nor)
- Disseminated sulphides
- Alignment of Plagioclase crystals show flow
- Two generations of plag: sub-rounded and elongated crystals



Micro-XRF imaging



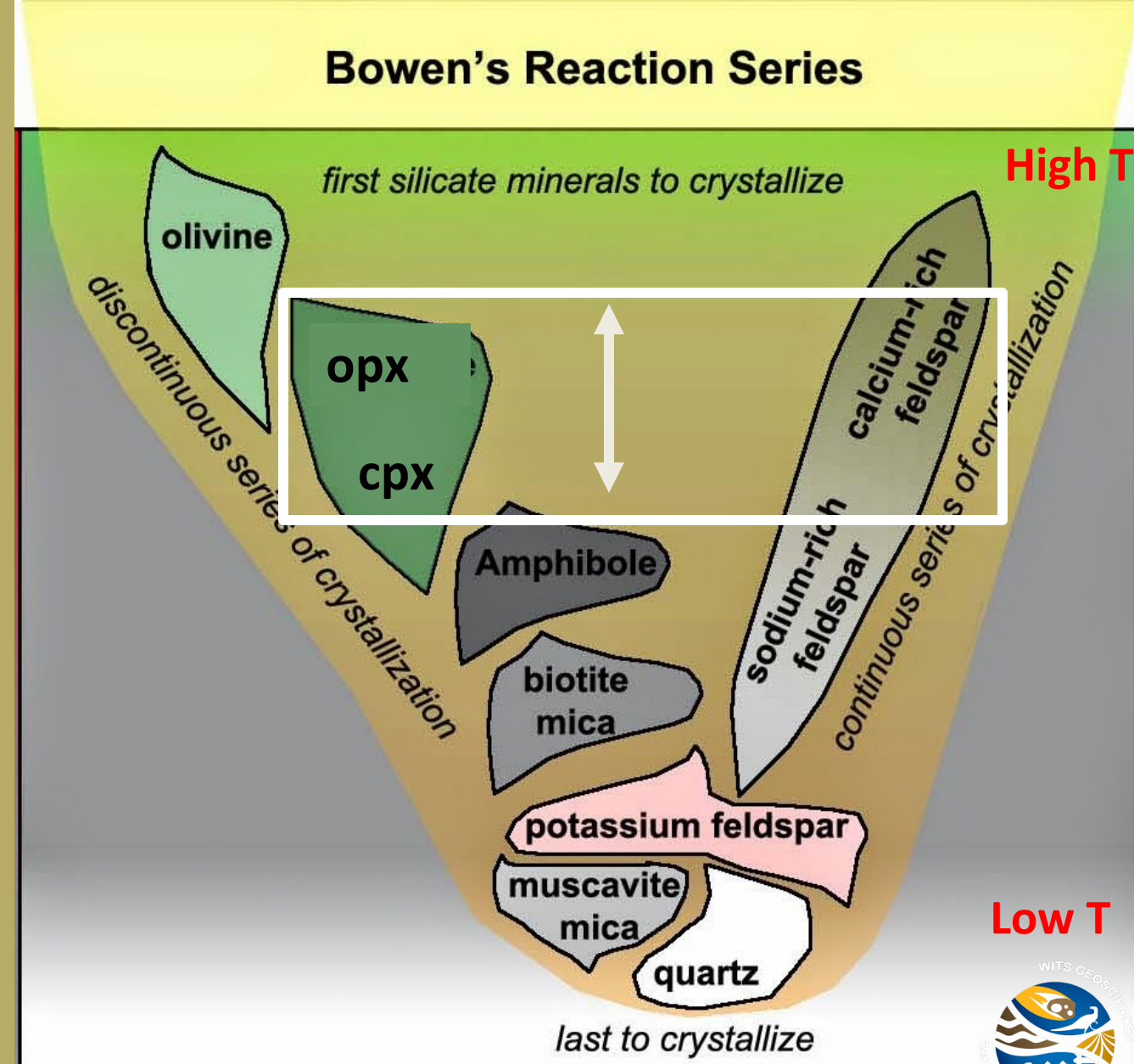
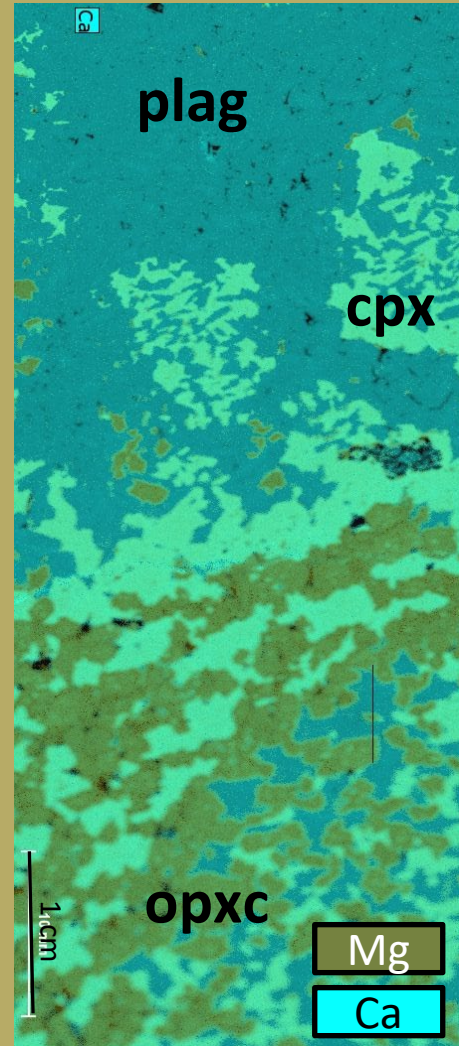
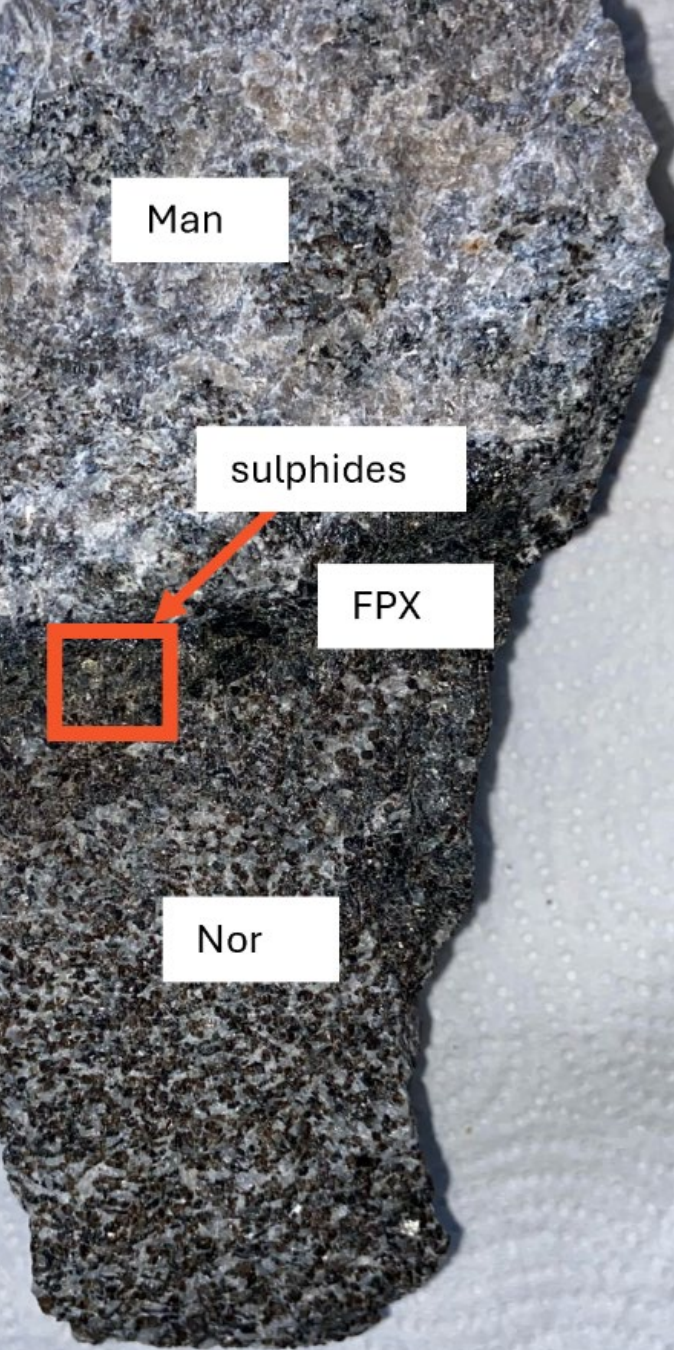
OPX $(\text{Mg,Fe})\text{SiO}_3$

CPX $(\text{Ca,Mg,Fe,Na})(\text{Mg,Fe,Al})(\text{Si,Al})_2\text{O}_6$

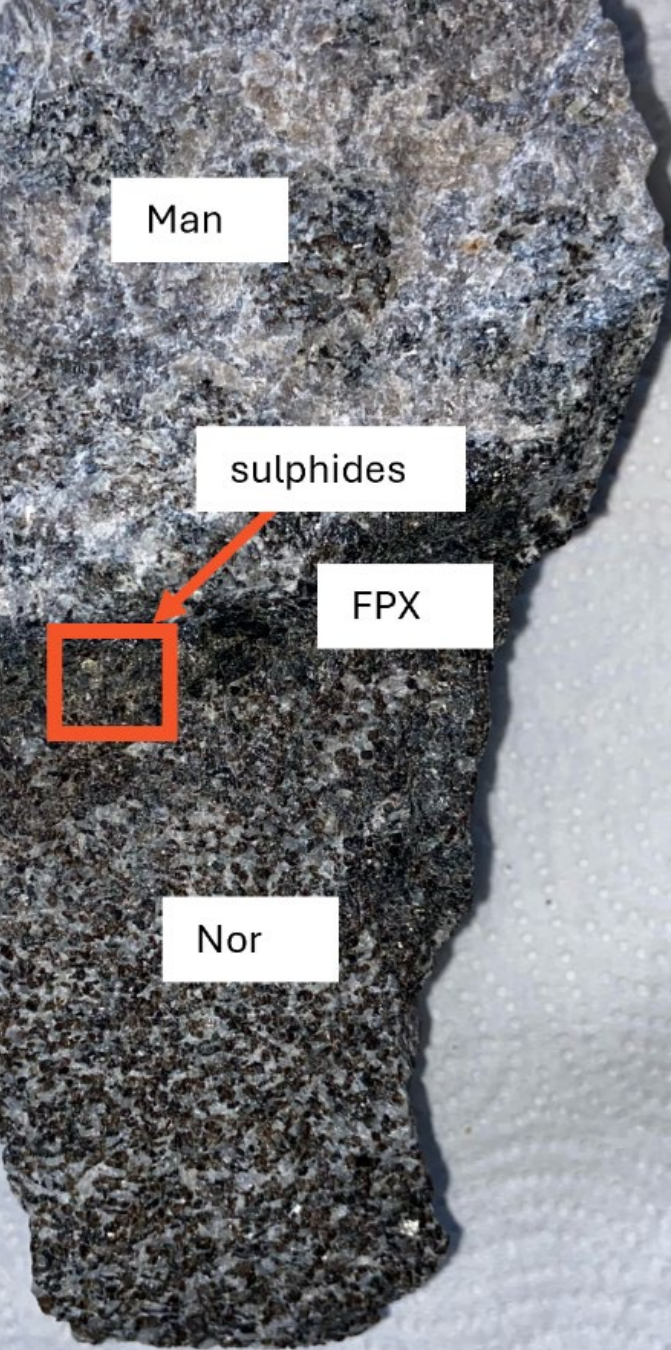
Oikocrysts: larger mineral that hosts different smaller mineral crystals

- Mottled anorthosite dominated by clinopyroxene **oikocrysts**
- Cpx rimming opx grains

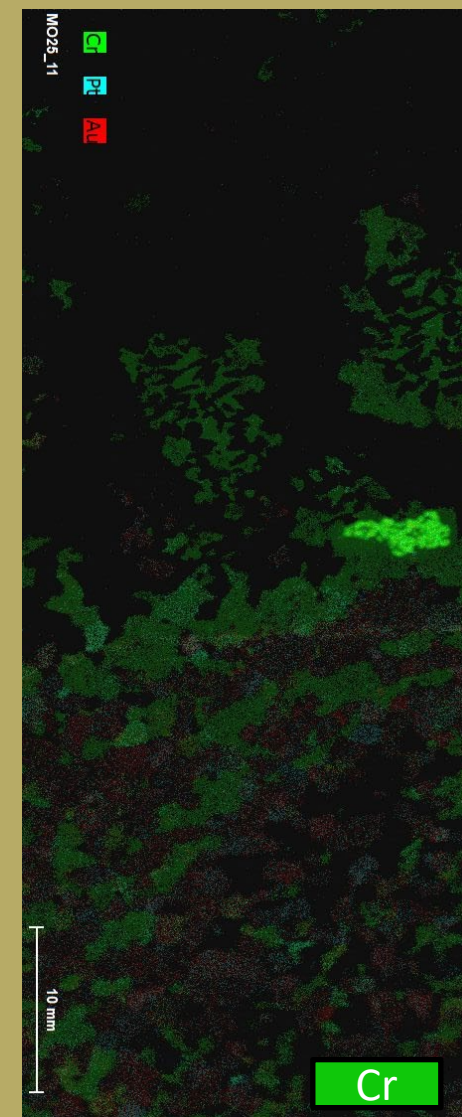
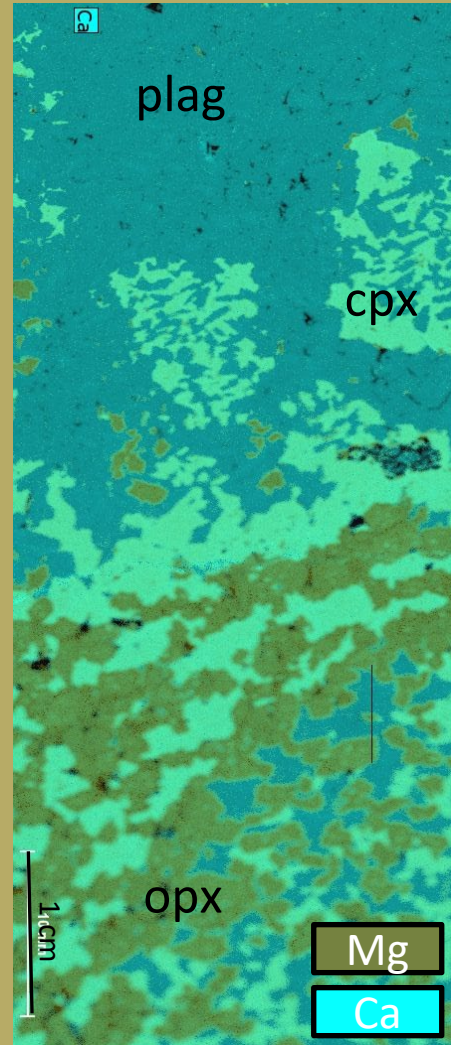
Micro-XRF imaging



Low T



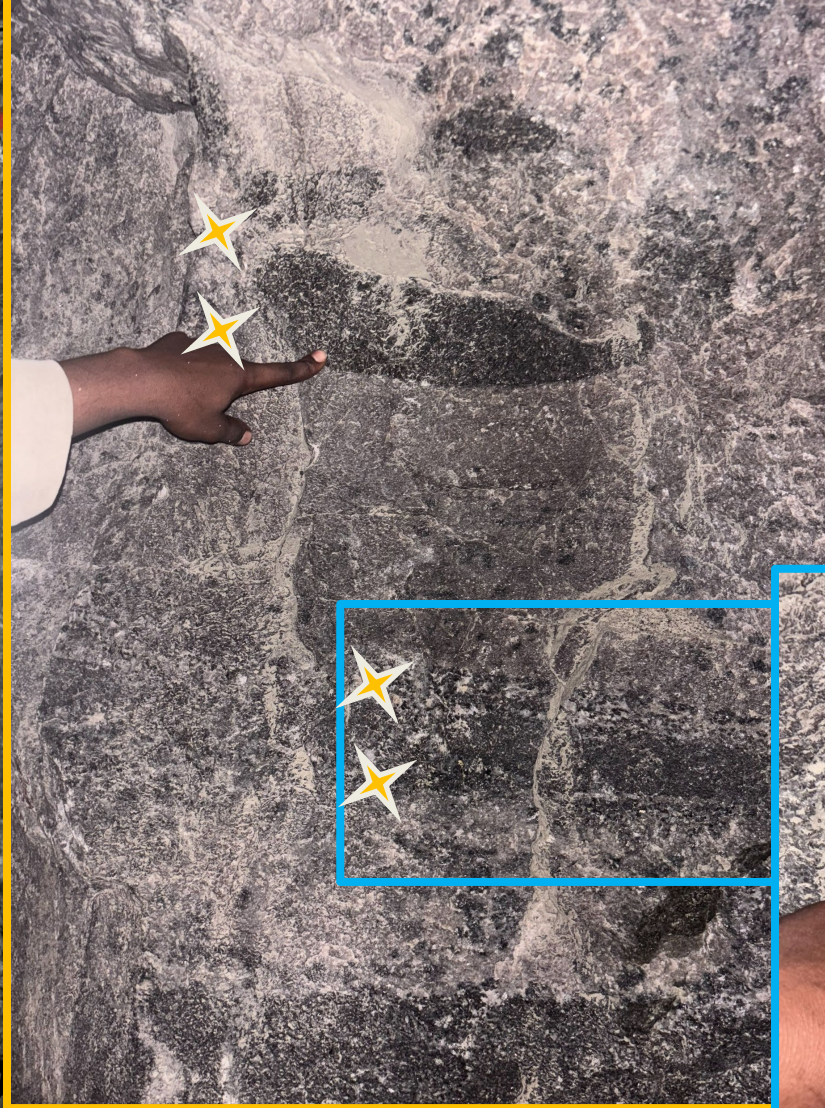
Micro-XRF imaging



- Chromitite cloth at the contact between anorthosite and pyroxenite
- Sulphides disseminated within cpx

Merensky felspathic pyroxenite boulder within mottled anorthosite

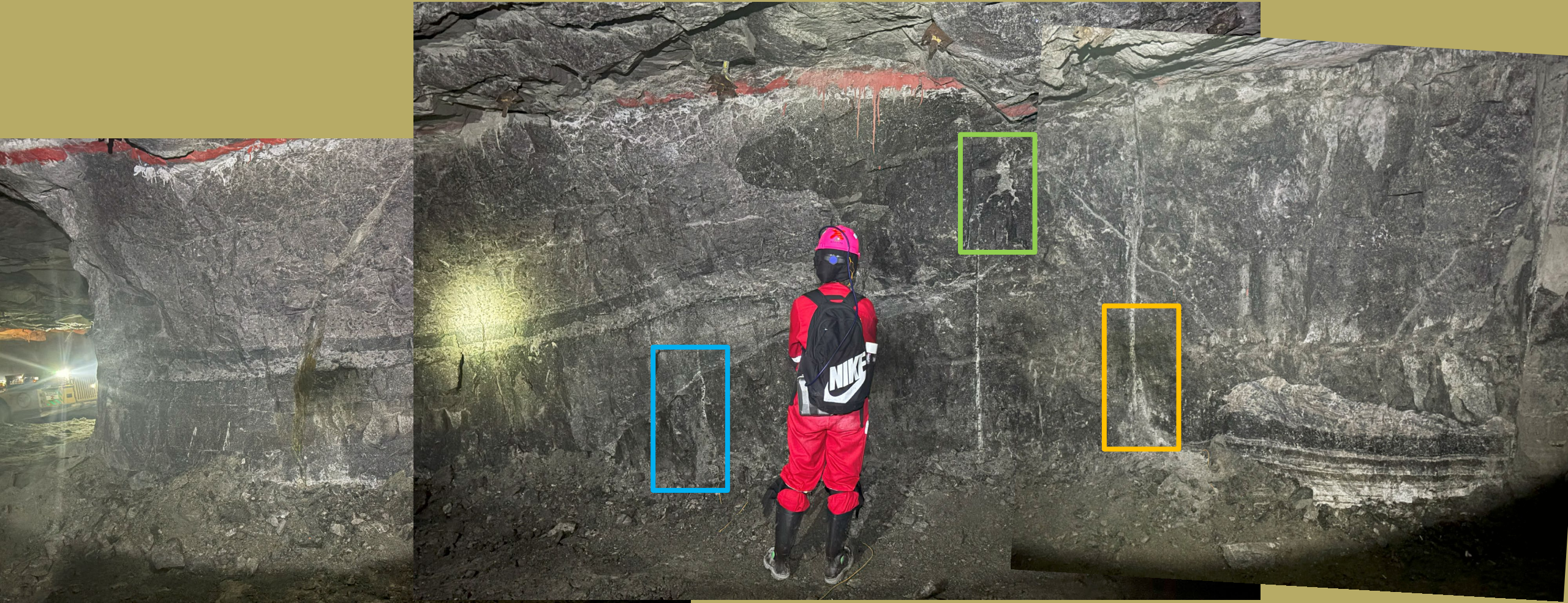




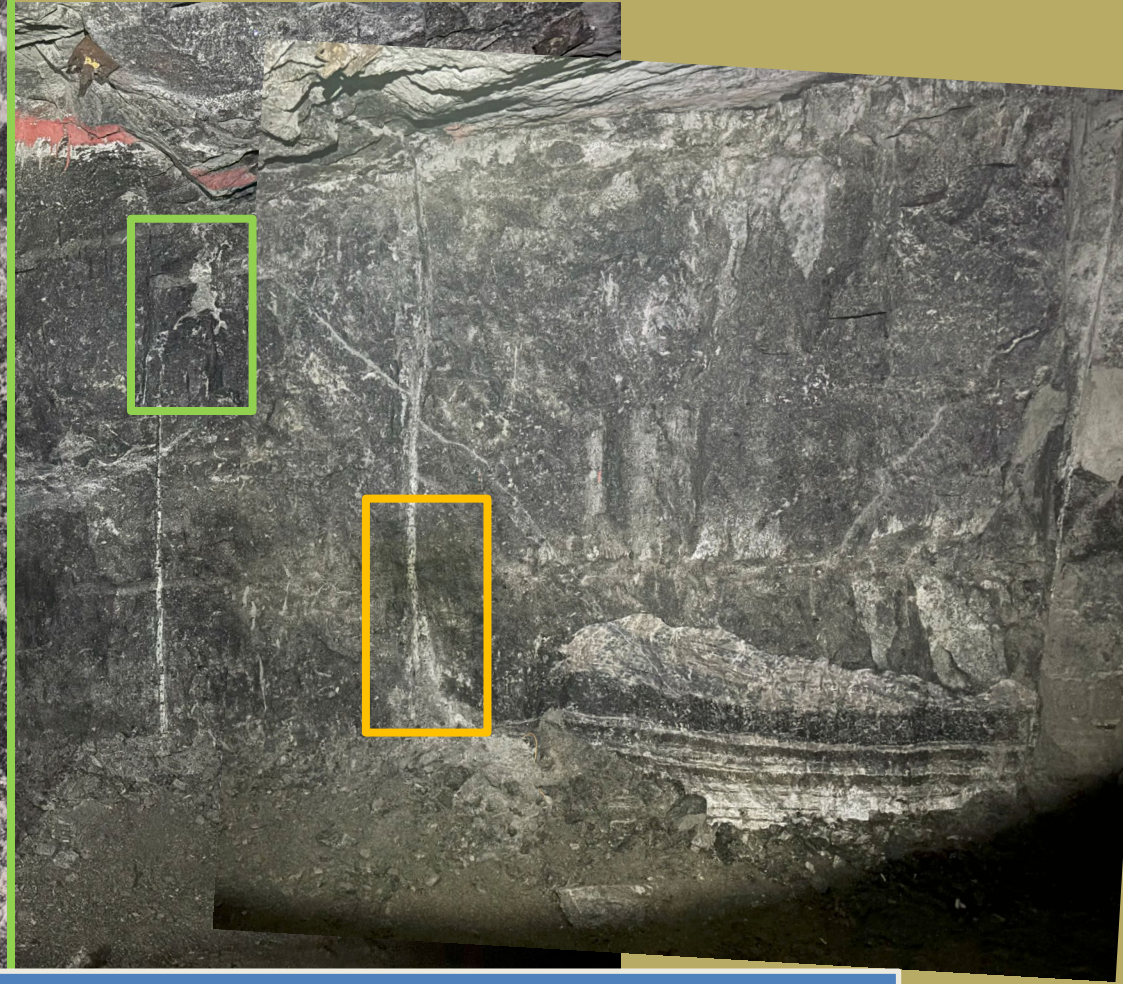
- Diffuse contacts
- Magmatic reaction and assimilation of pyroxenite into mottled anorthosite
- Sulphides in magmatic reaction/assimilation haloes



Behaviour of late vertical pegmatitic dykes within Merensky feldspathic pyroxenite

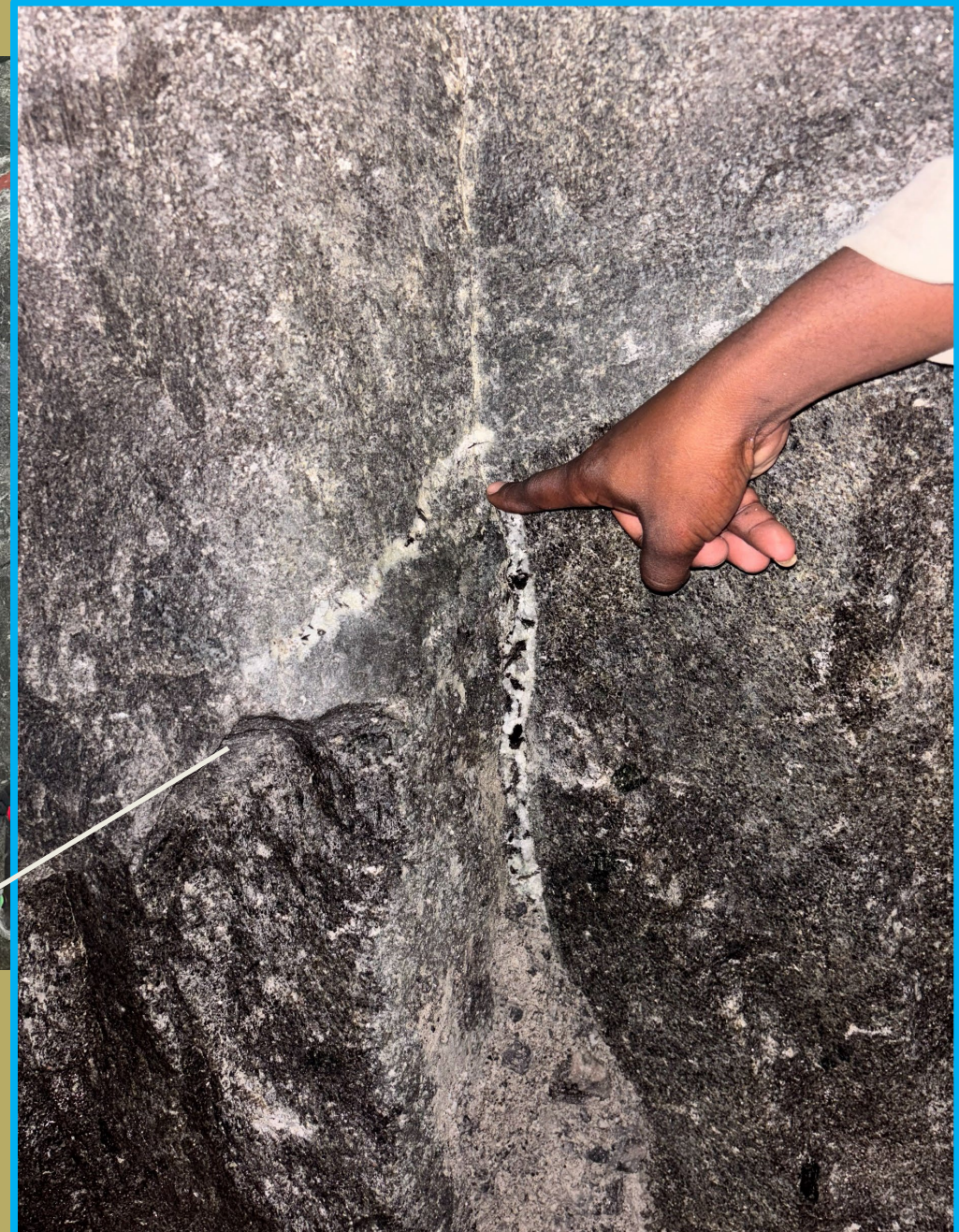


Dyke stops its progression upward creating a mushroom-like top



Before stopping dyke deviates from its vertical path, forming jogs

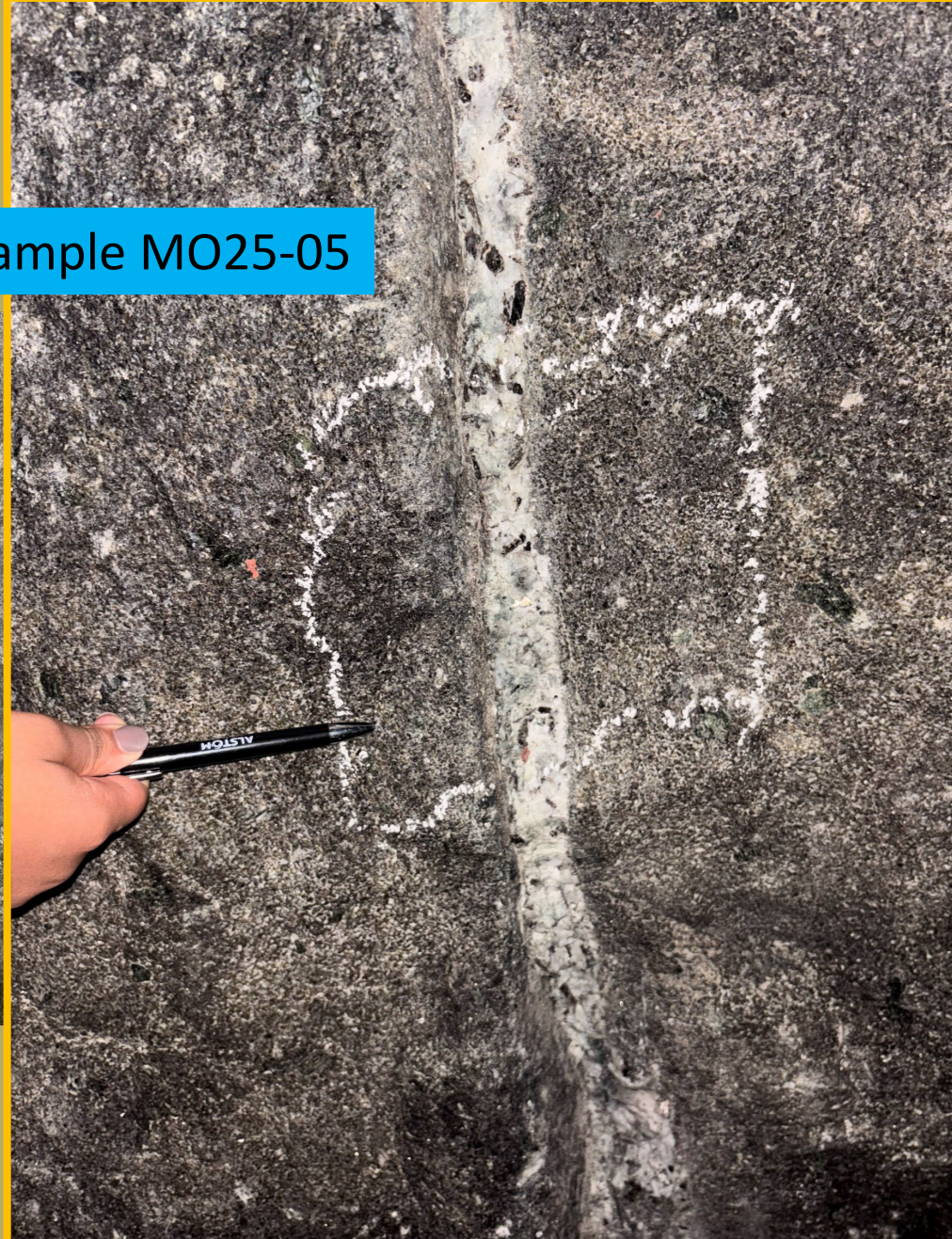
Behaviour of late vertical pegmatitic dykes within Merensky feldspathic pyroxenite



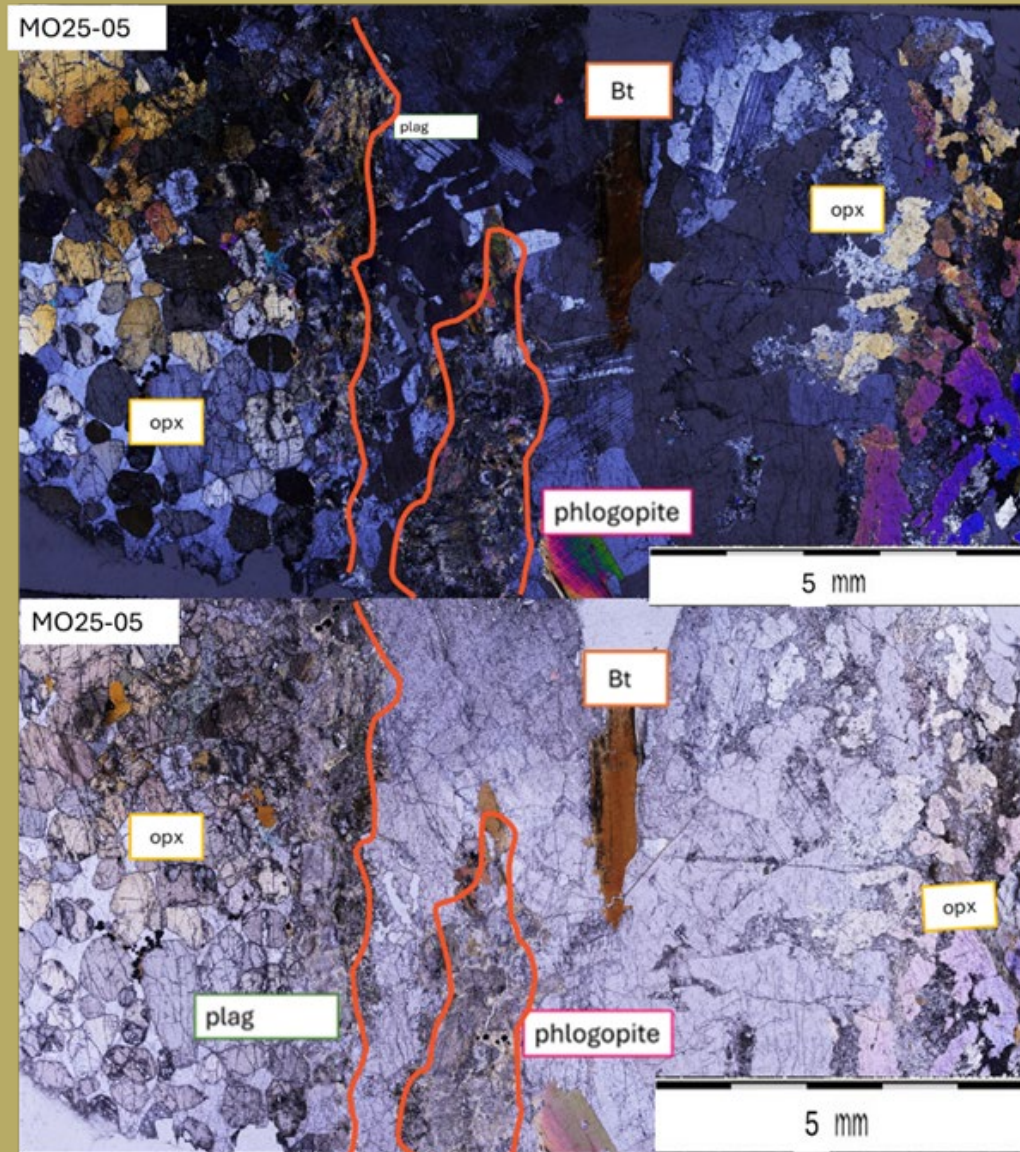
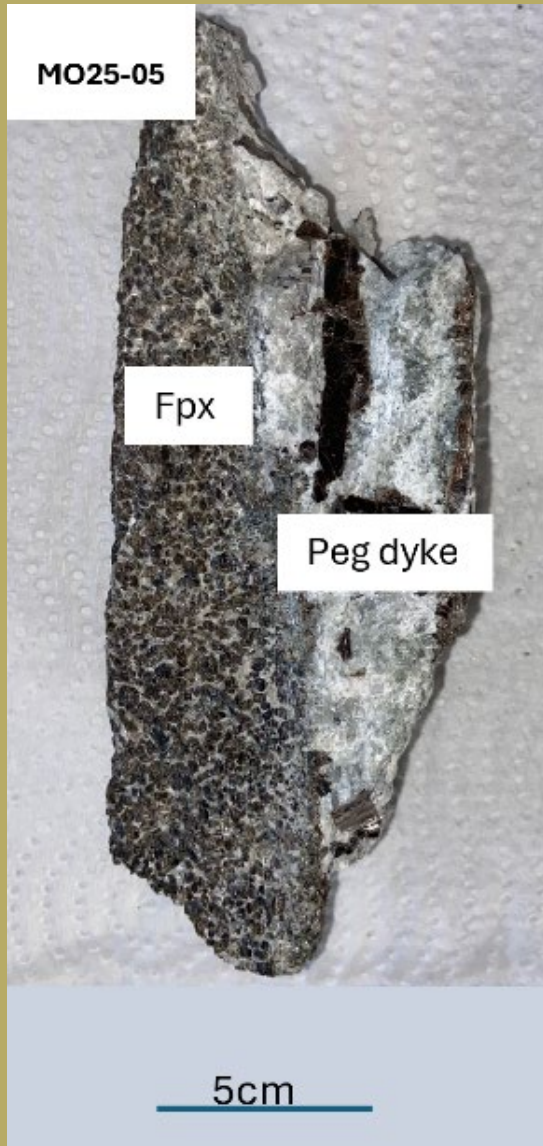
Dyke bending following contact between Merensky feldspathic pyroxenite and hybrid melanonorite

Late vertical pegmatitic dykes within Merensky felspathic pyroxenite

Sample MO25-05



Phlogopite-rich pegmatoidal dyke intrusion

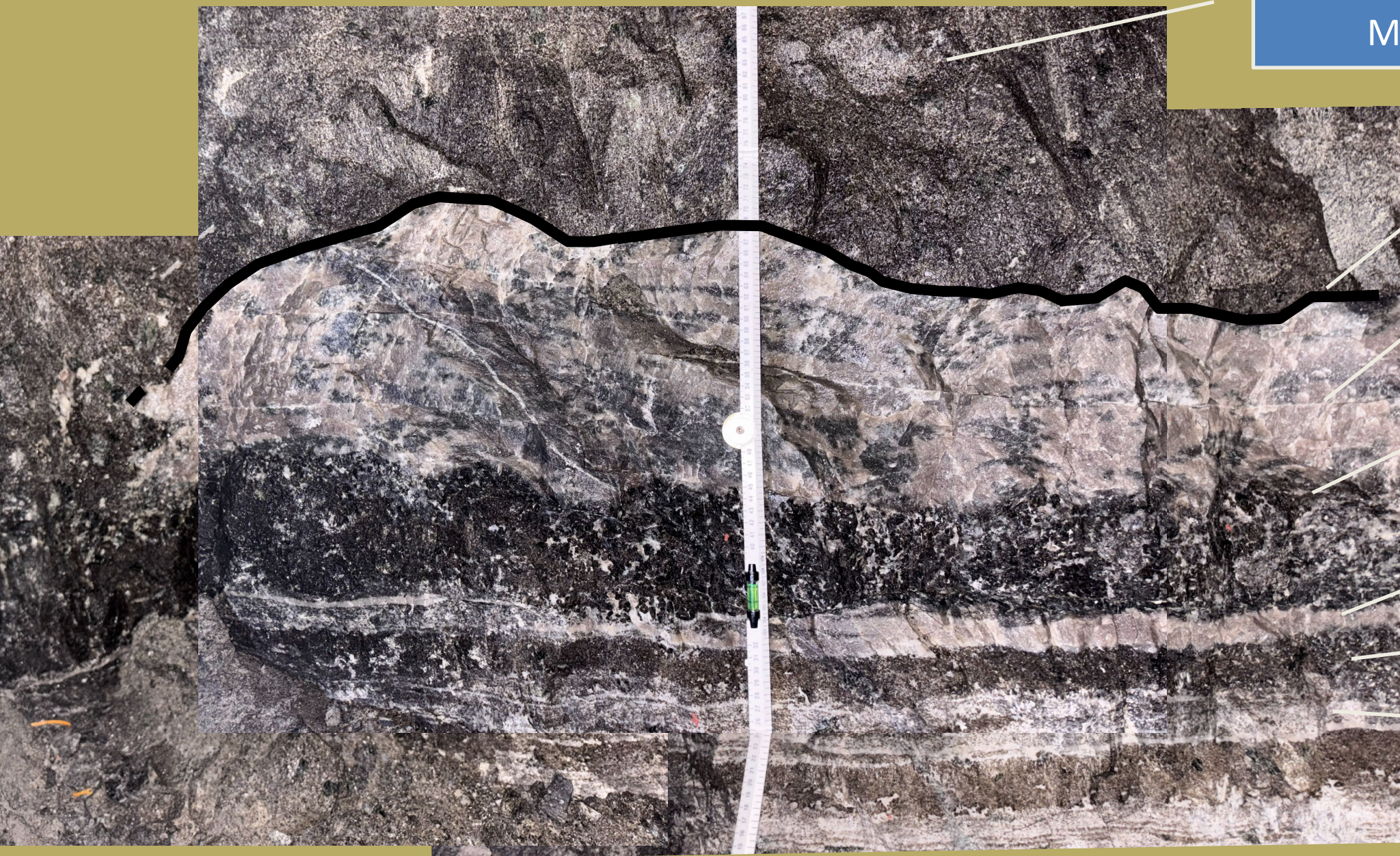


- Contact between the pegmatoidal dyke intrusion and the Merensky Reef feldspathic pyroxenite is not sharp
- Fragmented feldspathic pyroxenite within dyke
- Dyke consists of phlogopite-rich + plagioclase

Magmatic layering at the footwall of the Merensky felspathic pyroxenite



Magmatic layering at the footwall



Feldspatic pyroxenite
Merensky Reef

Chromitite
stringer

Mottled
Anorthosite

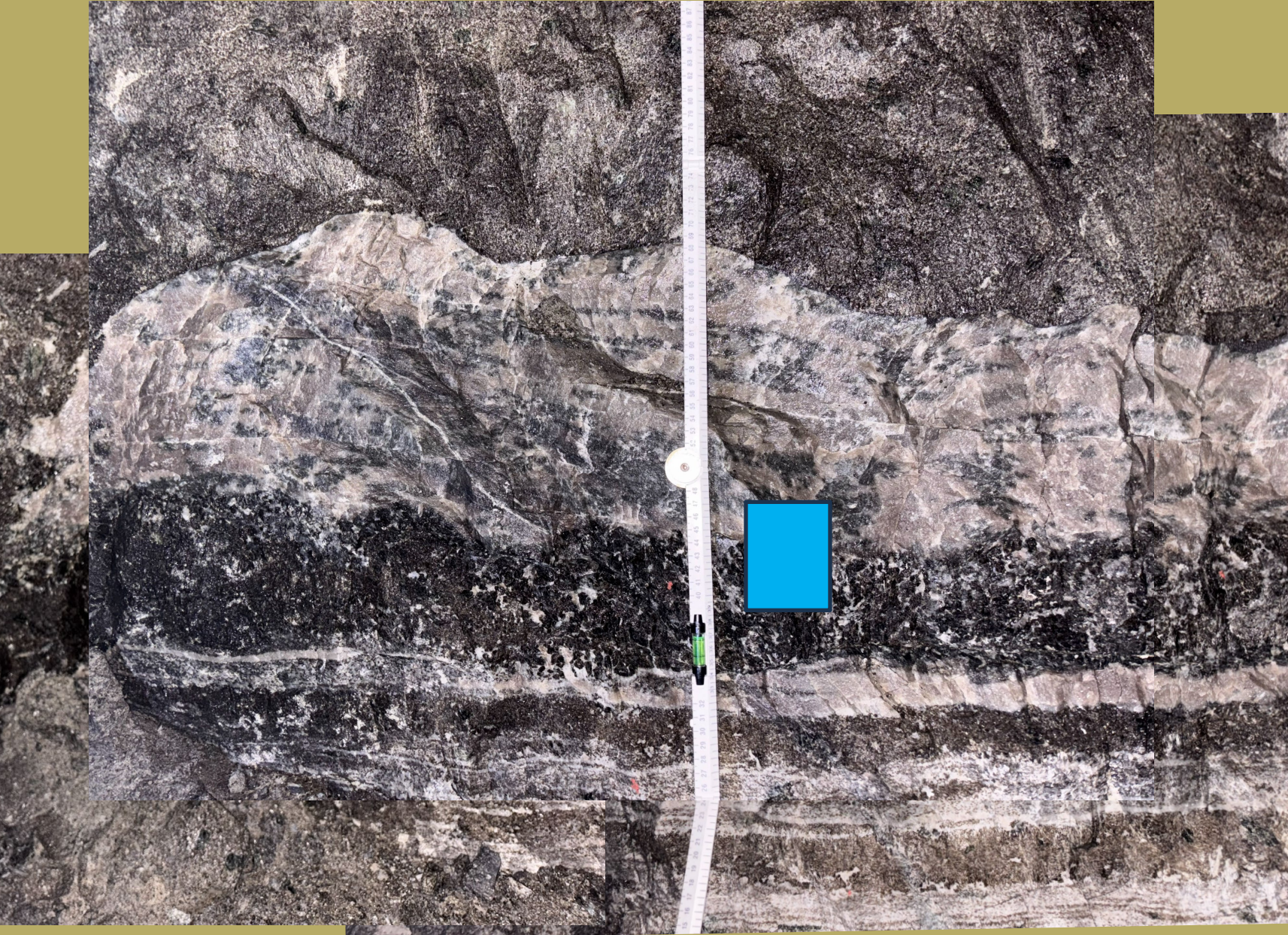
Pegmatoidal
pyroxenite

Anorthosite

Pyroxenite

Leuco
norite

Magmatic layering at the footwall



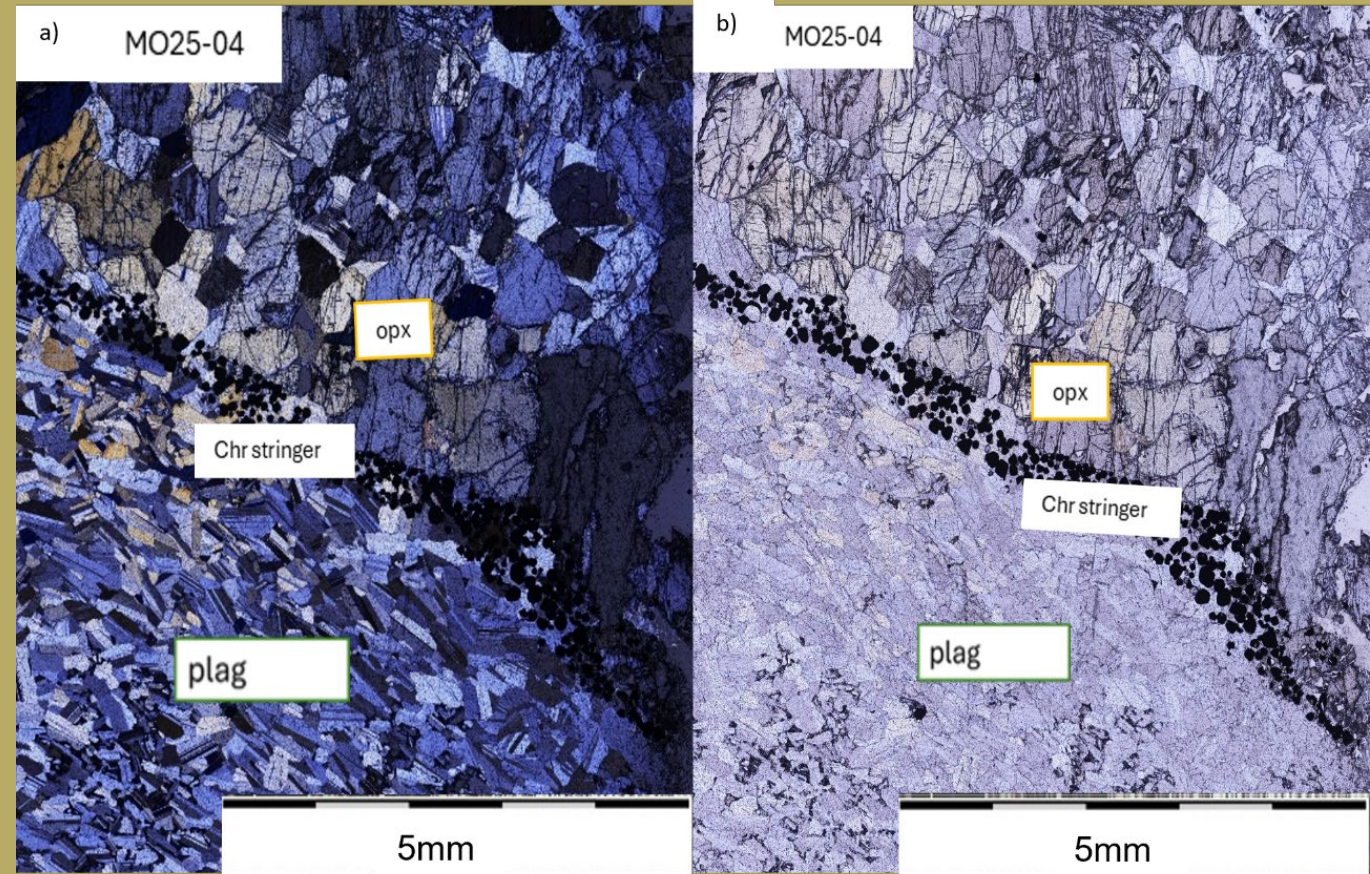
Sample MO25-04

MR Feldspathic
pyroxenite

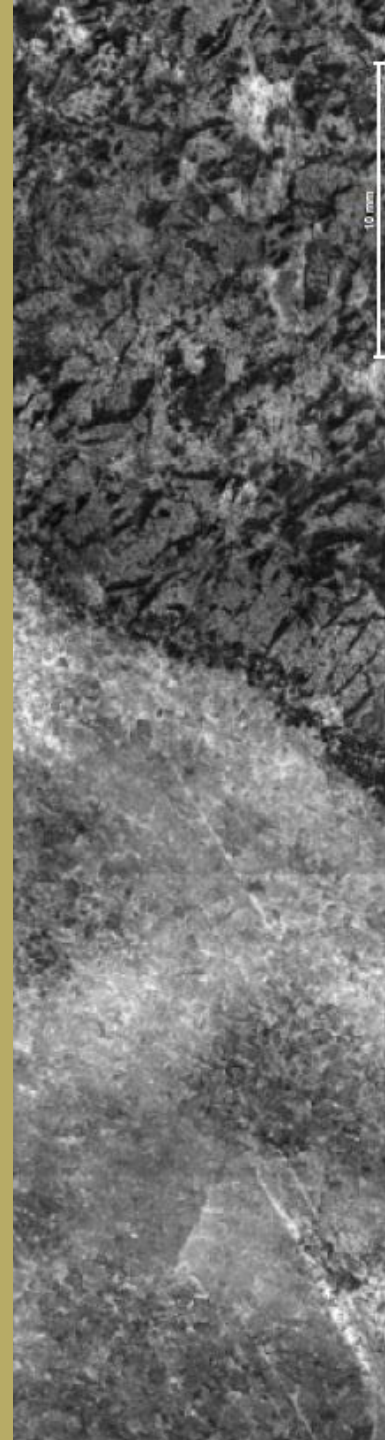
Chromitite stringer

Mottled
anorthosite

Sample MO25-04



- Sharp undulating contact between the FPX and MAN
- Chromite stringers consist of rounded grains
- Disseminated fine-grained chromite grains within intracumulus plag in FPX
- No chromite grains in MAN
- Plag slaths parallel to contact and chromitite stringers

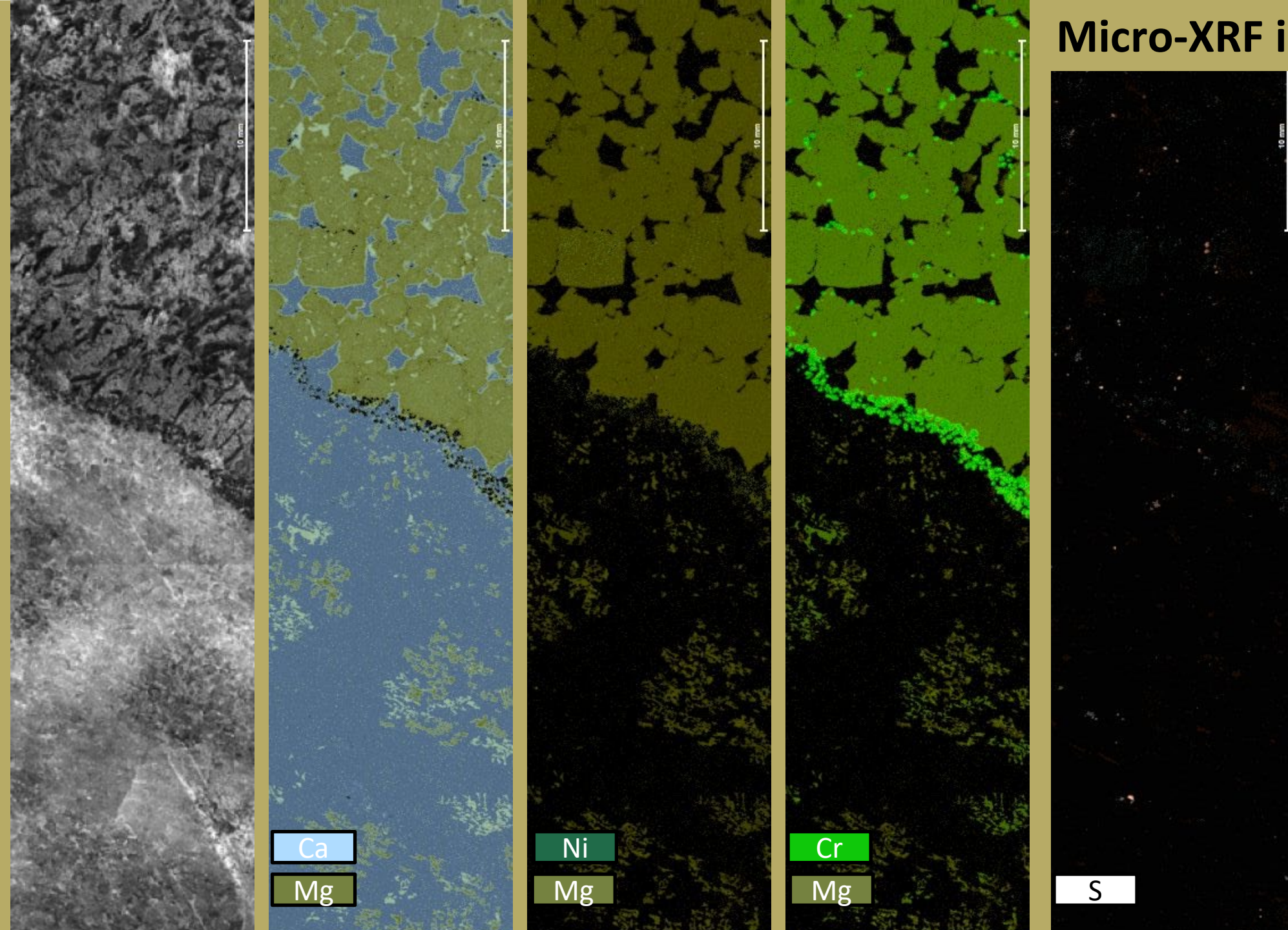


Micro-XRF imaging

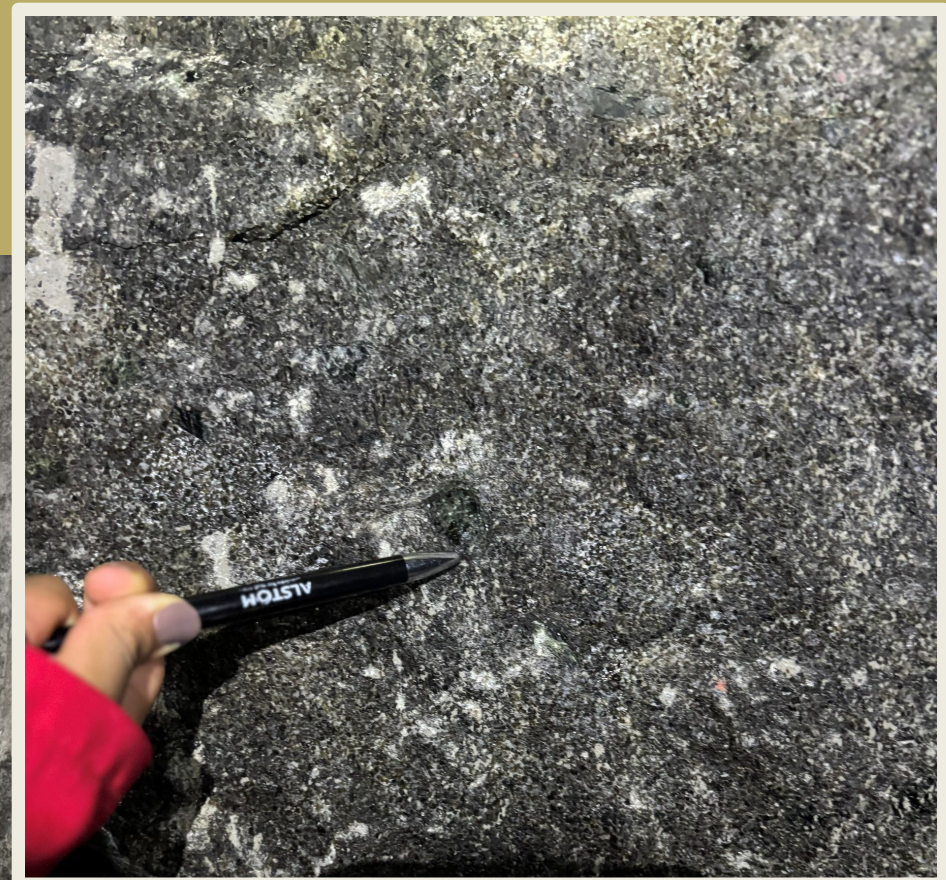
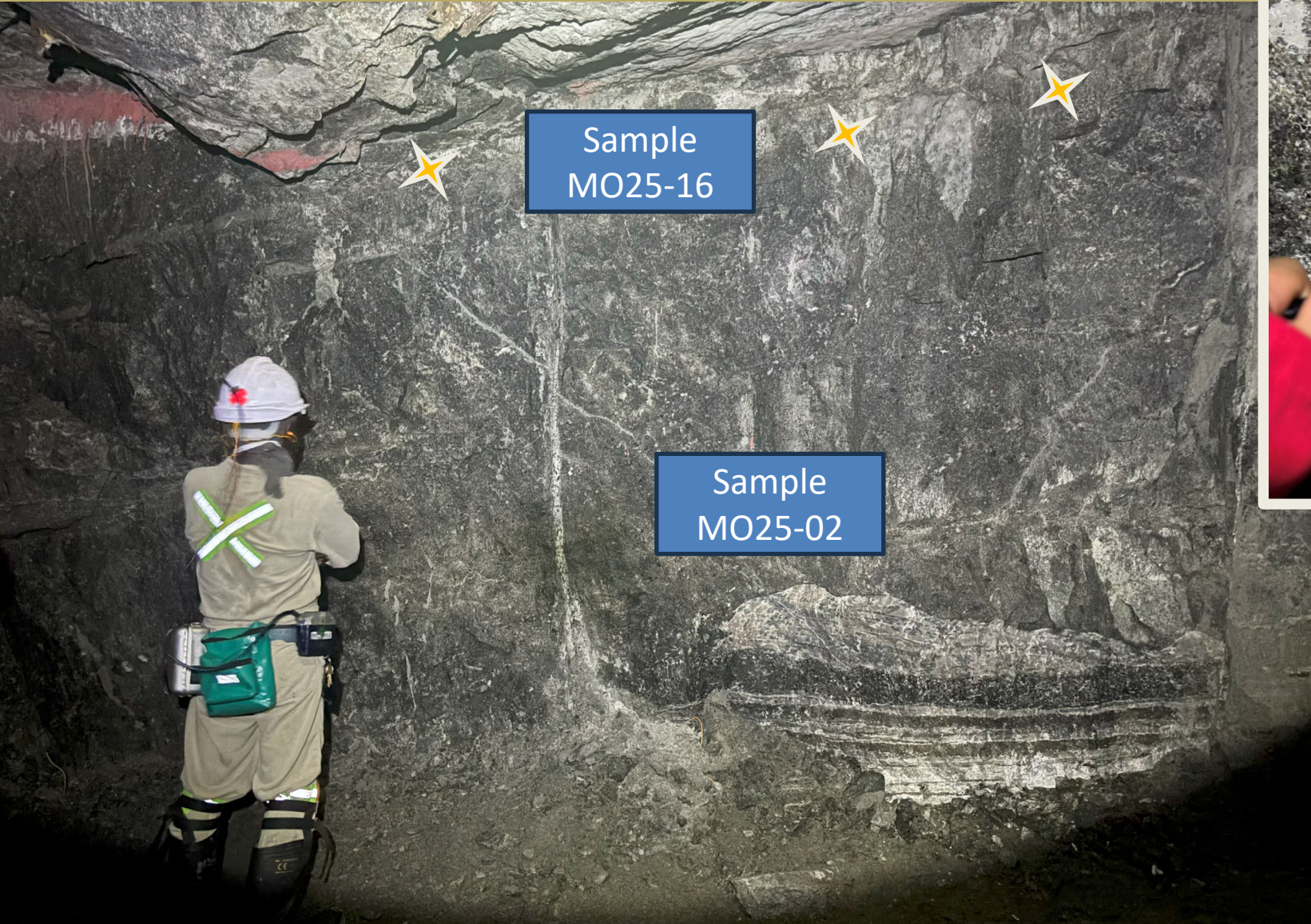


- Cpx halo around subhedral cumulus opx
- Disseminated Cpx lamella within opx grains
- Chromitite stringer mostly hosted by plagioclase
- Disseminated fine-grained chromite grains in FPX with plagioclase and at the margin between opx
- MAN is after the Chromitite stringer formation
- MAN intruded along chromitite stinger unconformity
- Oikocrysts = Mottles in MAN consist of both opx and cpx
- Mottles subparallel to contact

Micro-XRF imaging

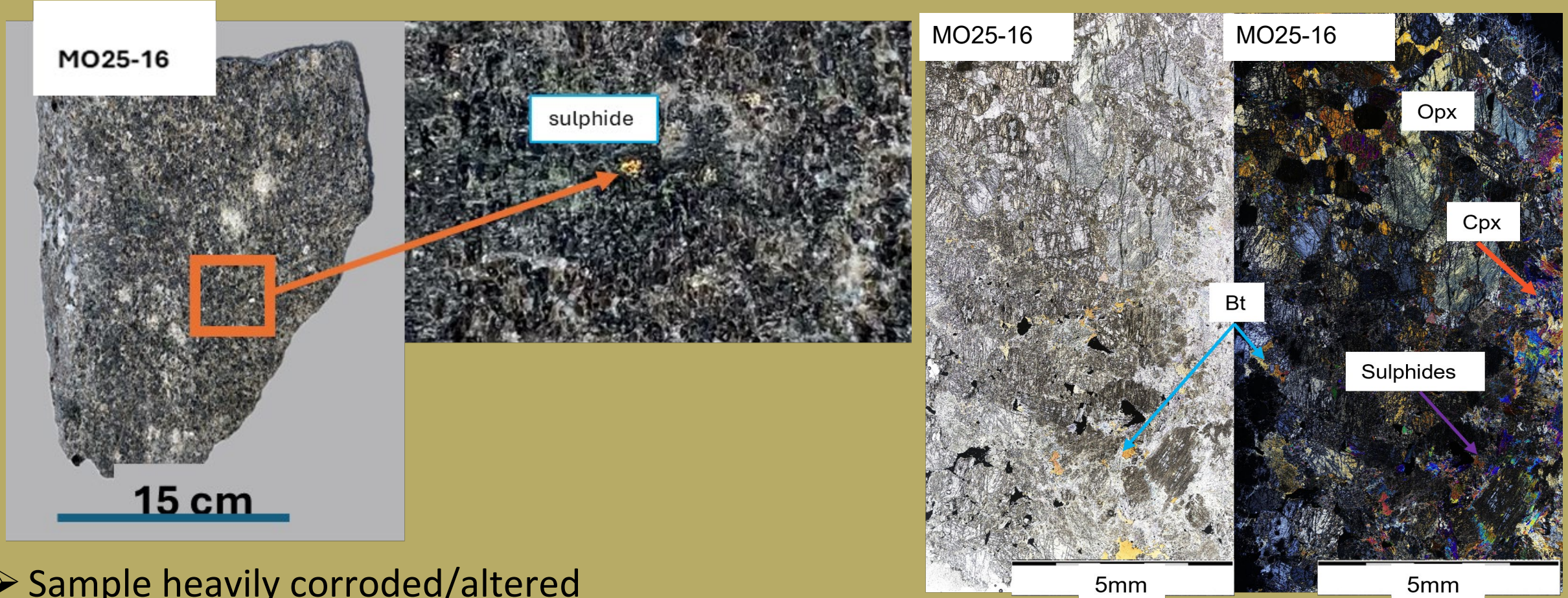


Merensky felspathic pyroxenite



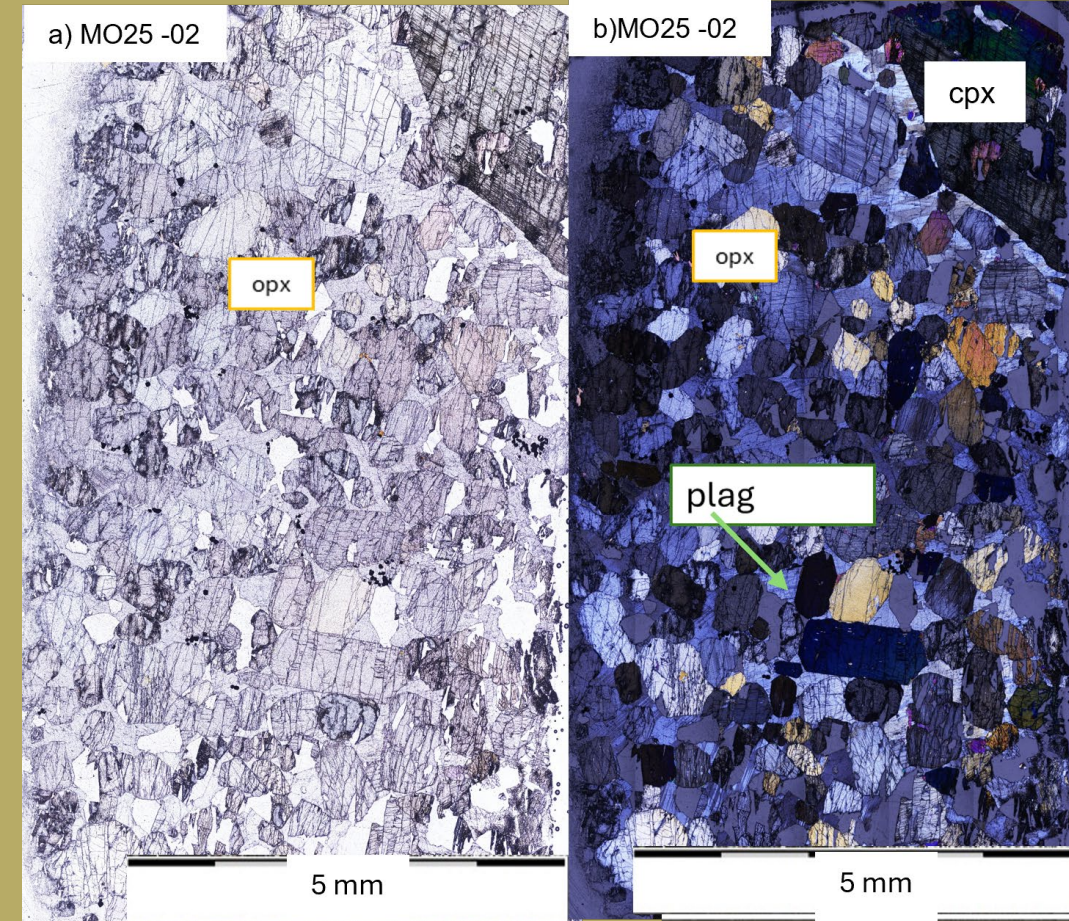
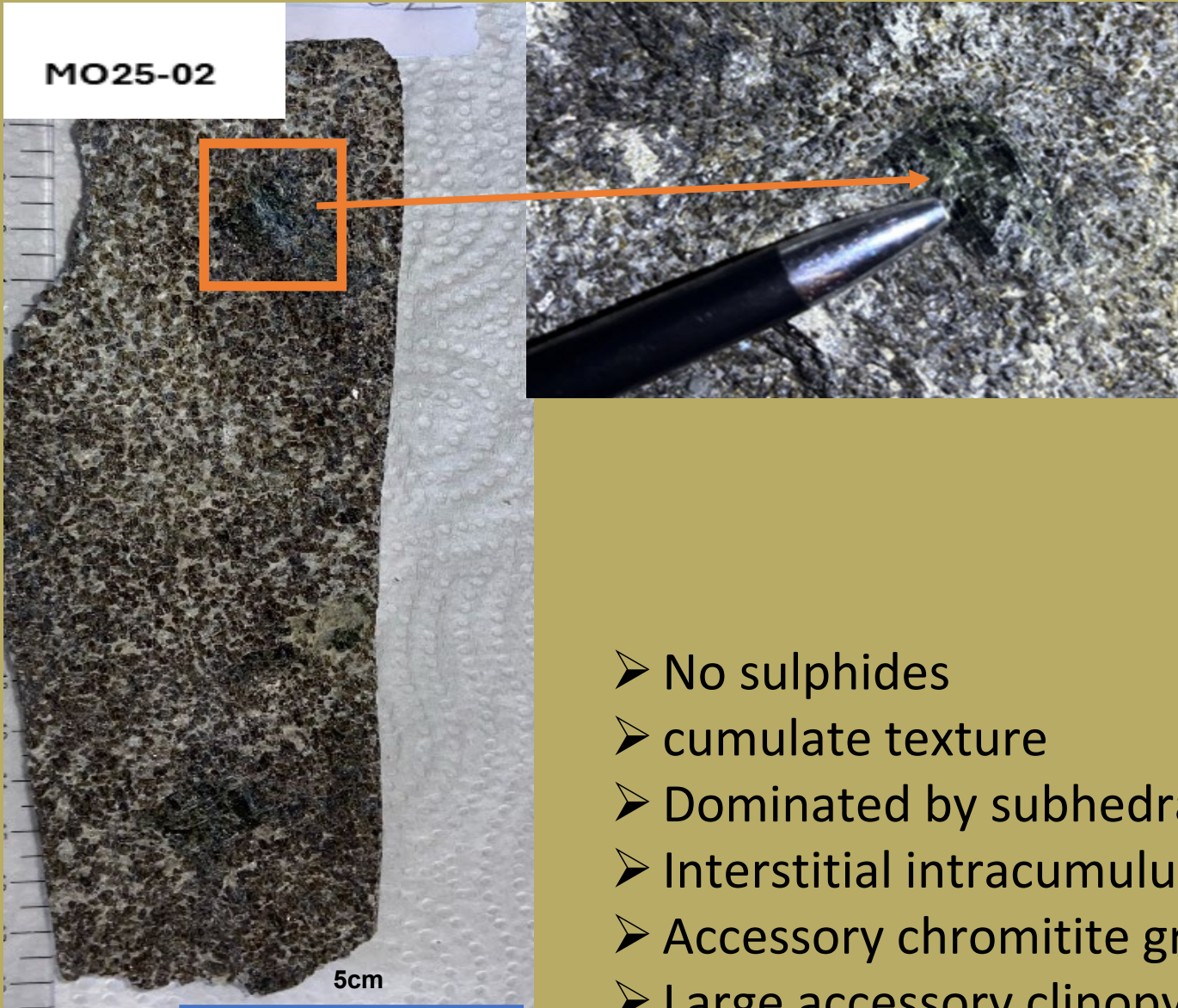
orthocumulate (framework of cumulus) opx crystals with interstitial plagioclase and large accessory cpx green phenocrysts
Sulphides + PGE at the top

Sample MO25-16 – Sulphide-bearing Merensky feldspathic pyroxenite



- Sample heavily corroded/altered
- Inhomogeneous, fractured orthopyroxenes
- Disseminated sulphides, mostly pentlandite with rims of chalcopyrite
- clinopyroxene exsolution lamellae and discontinuous rims around the cumulus orthopyroxene

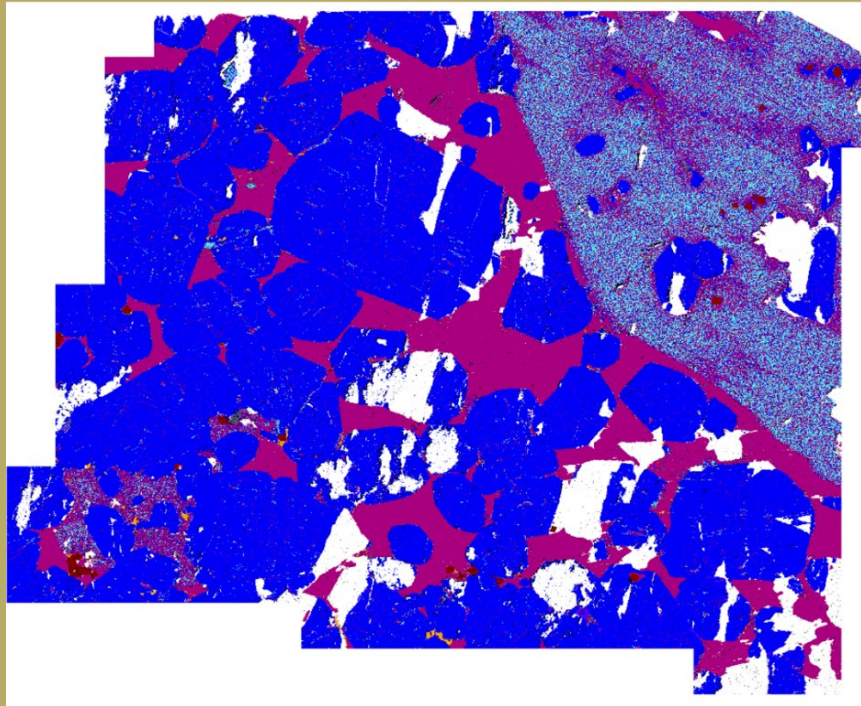
Sample MO25-02 – Sulphide-devoid Merensky feldspathic pyroxenite



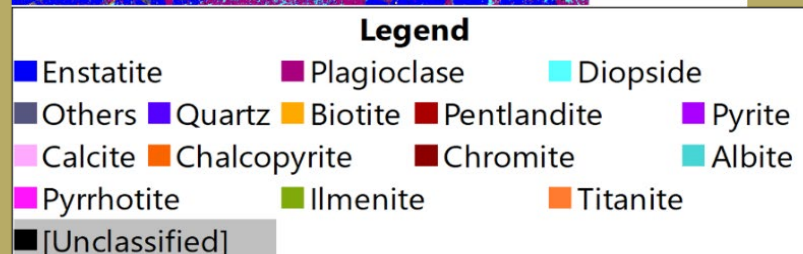
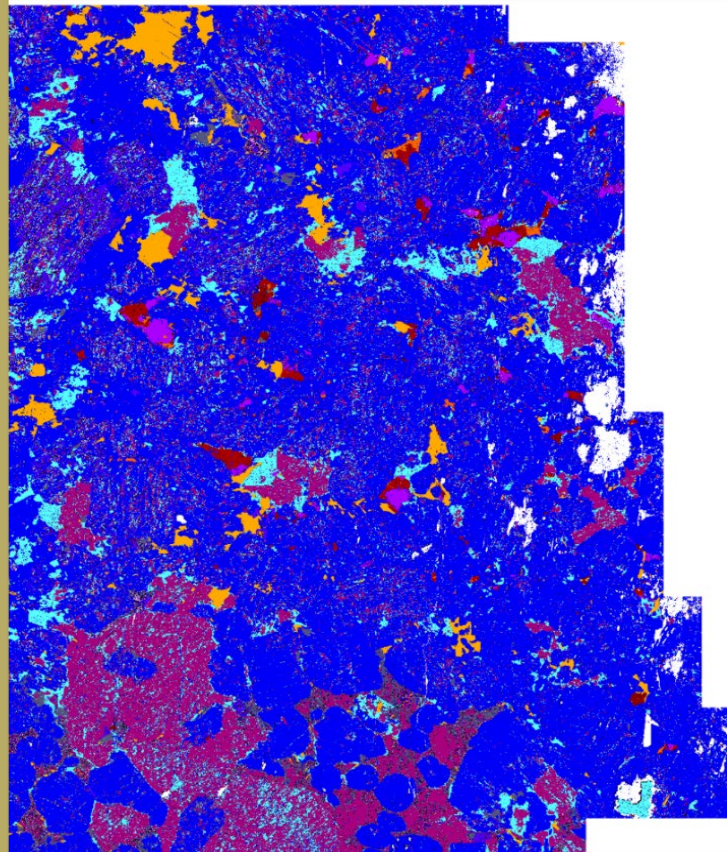
- No sulphides
- cumulate texture
- Dominated by subhedral cumulus orthopyroxenes
- Interstitial intracumulus plagioclase
- Accessory chromitite grains within interstitial plag
- Large accessory clinopyroxene subhedral crystals

TIMA Results: Comparisons of the Merensky Reef feldspathic pyroxenites

Sulfide-devoid sample
(MO25-02)

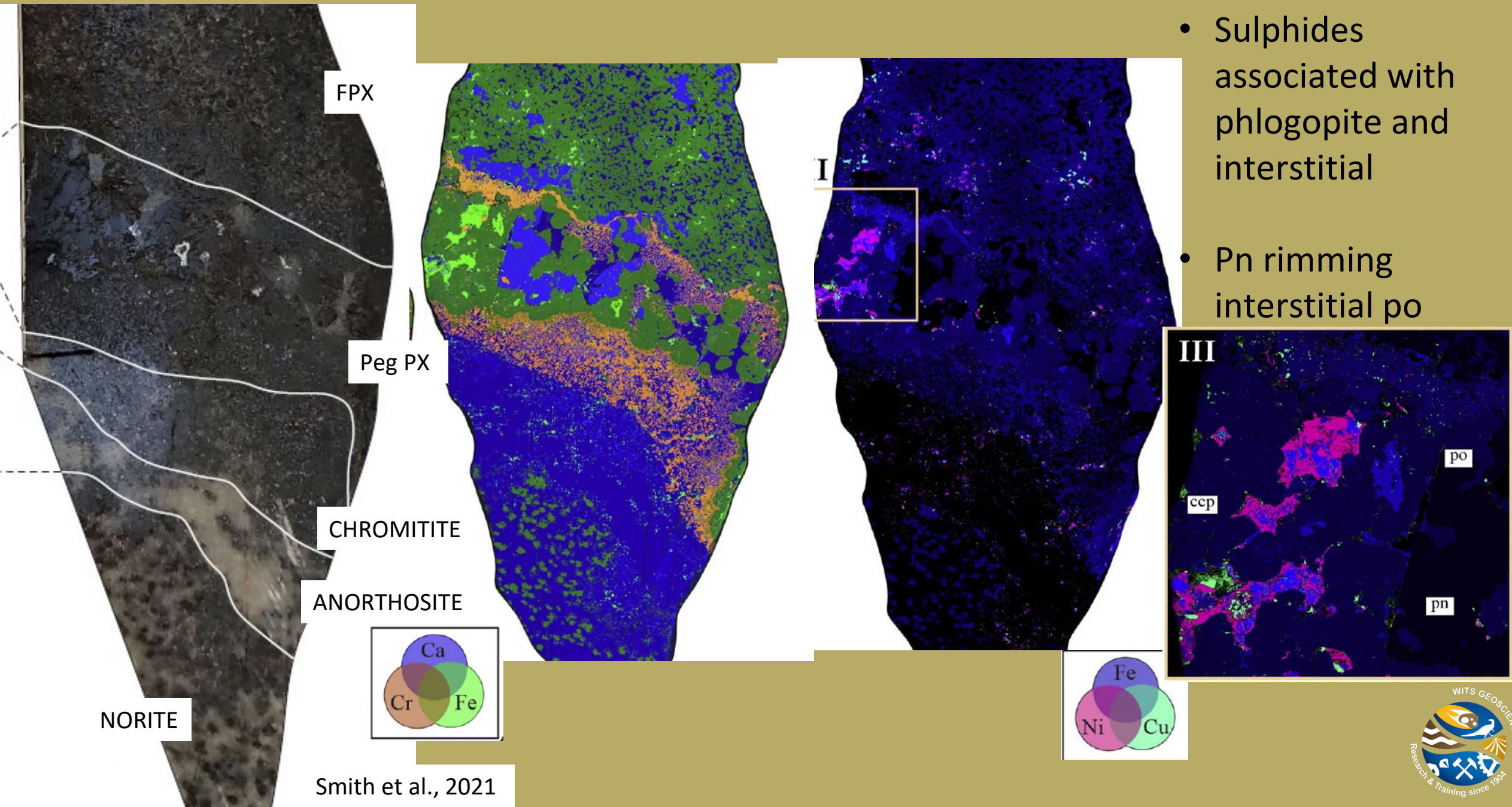


Sulphide-rich sample
(MO25-16)

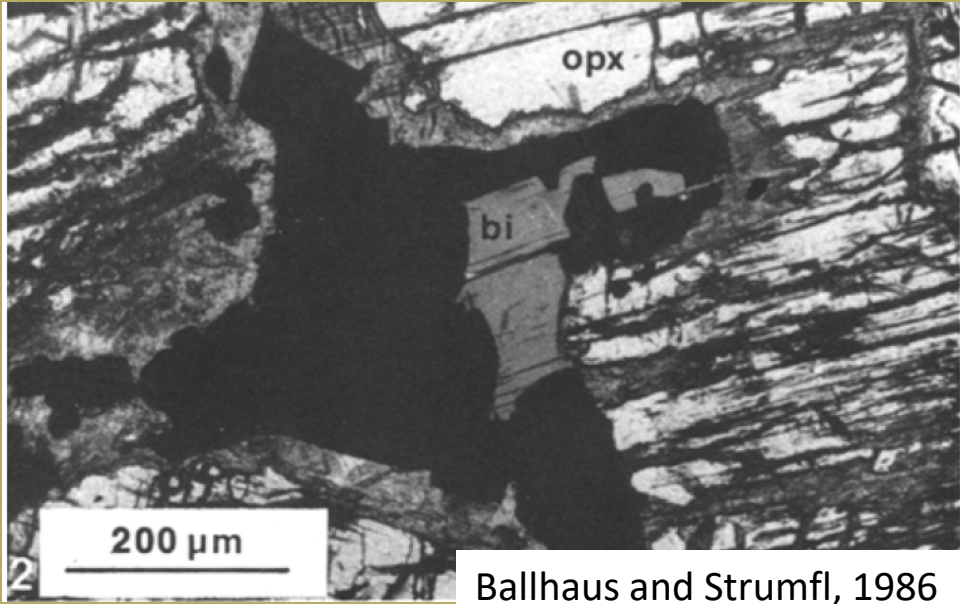


- Corrosion due to alteration and replacement of primary magmatic opx and plag by cpx
- Biotite, sulphides and minor accessory minerals appear as interstitial as substituting the intercumulus plagioclase **possibly due to fluids/rock interaction**
- Sulphide-rich pyroxenite has very little disseminated chromite

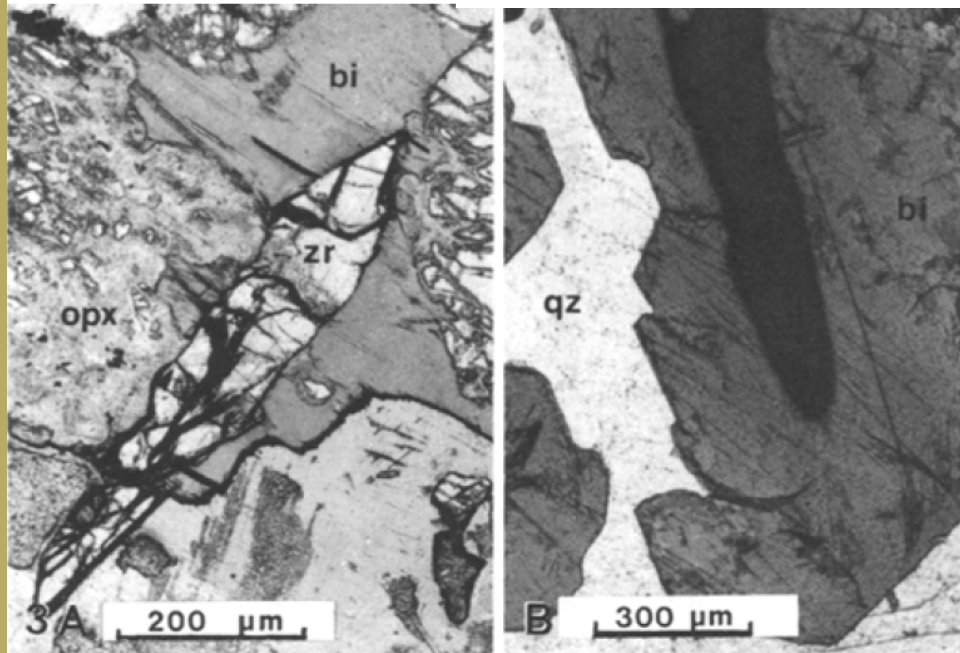
Maia Mapper Micro-XRF imaging pegmatoidal pyroxenite – Rustenburg



Association of sulfides with hydrous silicates is typical of MR

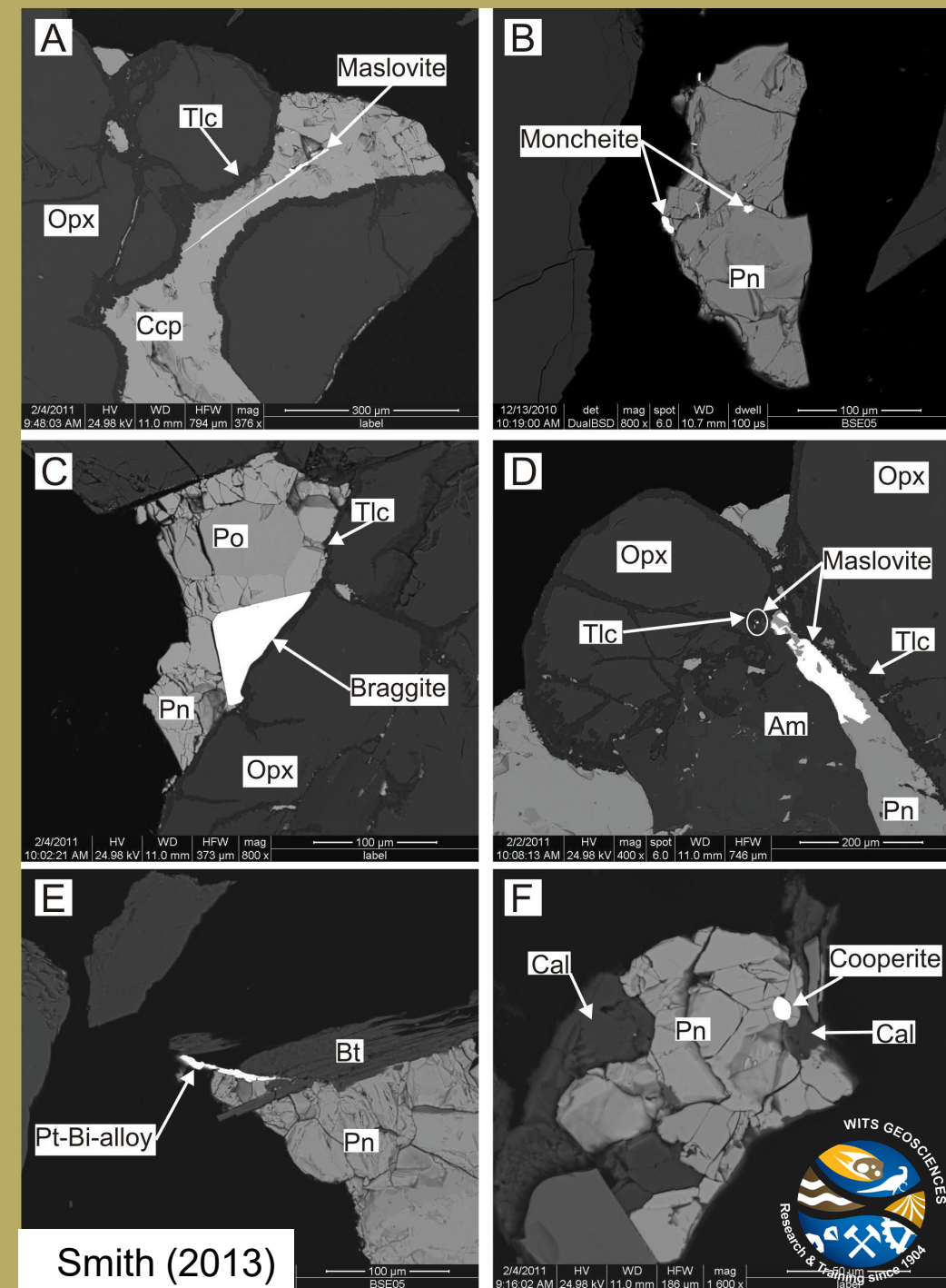


Ballhaus and Strumfl, 1986



- base metal sulfide grain (opaque) interstitial to cumulus opx, containing a biotite inclusion
- intense hydrous alteration of orthopyroxene to actinolite and talc around the sulfide grain and along cracks.
- Biotite not due to alteration
- Biotite crystallisation precedes sulfides solidification
- Biotite often has rutile (*dark*) and zircon (Zr) inclusions and associated with quartz
- **Plagioclase, the main intercumulus silicate of the Reef, undergoes specific alteration stages in the presence of sulfides and hydrosilicates**

- PGMs minerals (bright phases in the SEM images) occur mostly at the contact between silicates and sulphide aggregates
- typical PGM has grain size of 10 μm or less!
- average grade is 6 g/t PGE +Au, prill split:
 - 4.82 ppm Pt
 - 2.04 ppm Pd
 - 0.66 ppm Ru
 - 0.24 ppm Rh
 - 0.8 ppm Ir
 - 0.26 ppm Au
- dominated by Pt-Pd-Ru sulphides (40%)
- 11% Pt tellurides, 6% Pt arsenides
- 40% PGE-Fe alloys, 3% Au-Ag alloy (electrum)



Observations record a complex magmatic evolution :

1. Sill-like Intrusion and crystallisation of mafic melt into magma chamber with fractionated (plag-rich) resident melt

2. Formation of chromitite stringers as reactions

3. Reheating of the feldspathic orthopyroxenite and formation of cpx exsolution lamellae and haloes in opx

4. Crystallisation led to the concentration of incompatible and fluids/vapor which triggered alteration of plag and sulphides precipitation

5. Intrusion of pegmatoidal pyroxenite as hangingwall and footwall

6. Injection of mottled anorthosite as a melt-slurry and turbulent disturbance of the reef

7. Formation of hybrid melanonorite, as assimilation of feldspathic pyroxenite into anorthosite

8. Intrusion of vertical phlogopite-rich pegmatoidal dykes

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Can these observations from one location be applied to explain the formation of the Merensky Reef across the whole Bushveld Complex?



Thank you!

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