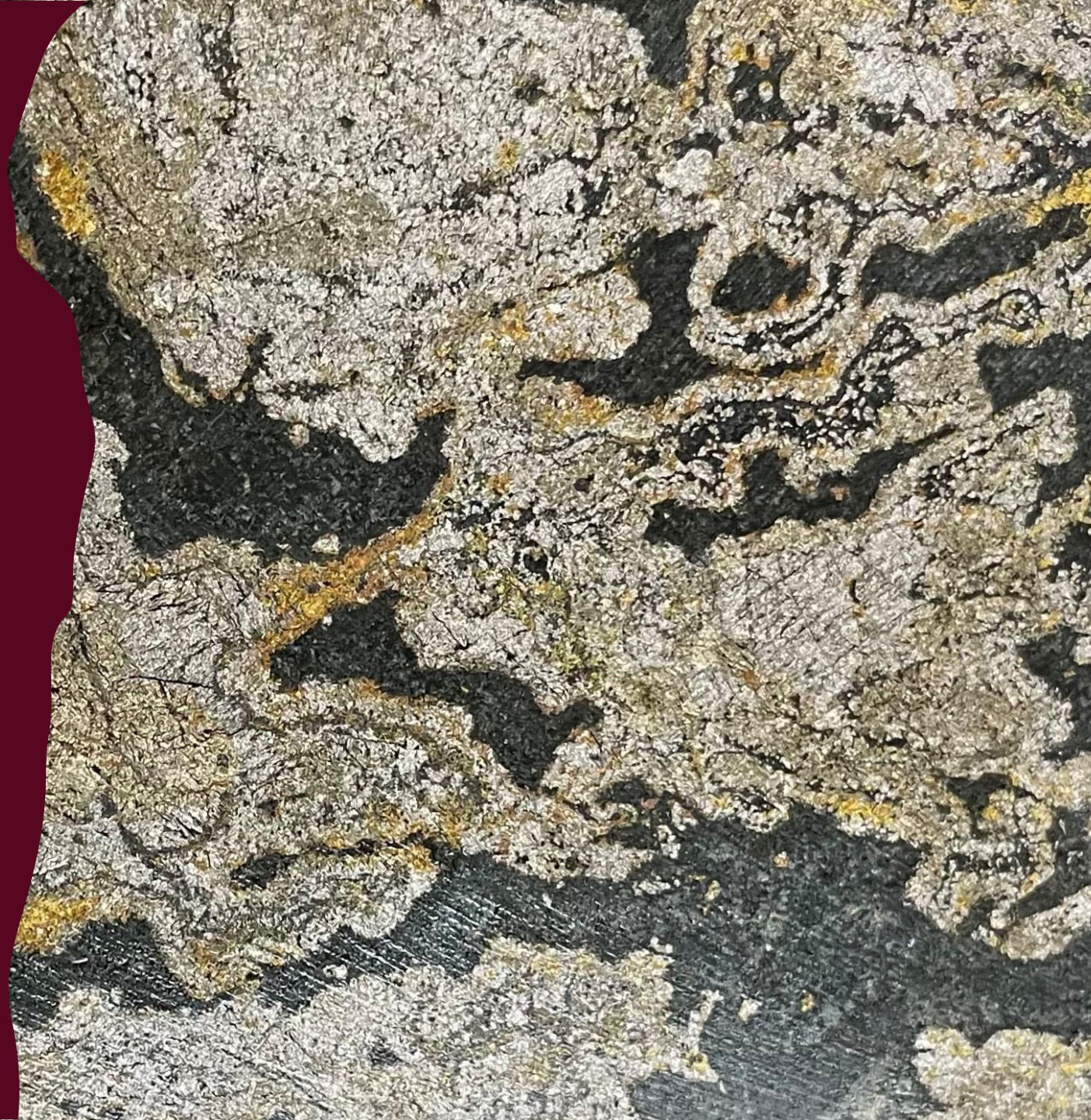
Connecting research and exploration for Ni-Cu-PGE sulfides at the continent, camp and deposit scale

What are we using and what do we need?

August 2024

RioTinto



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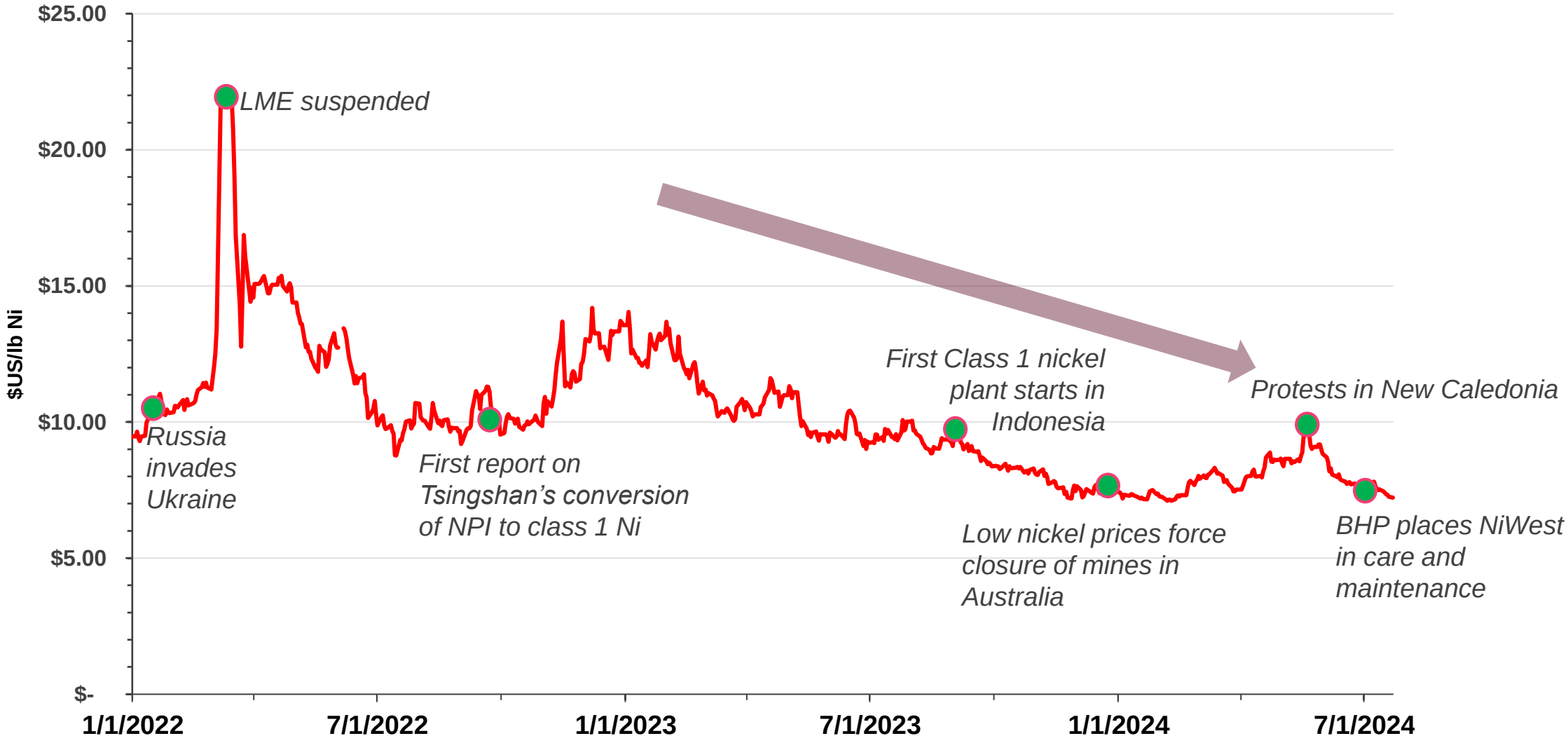
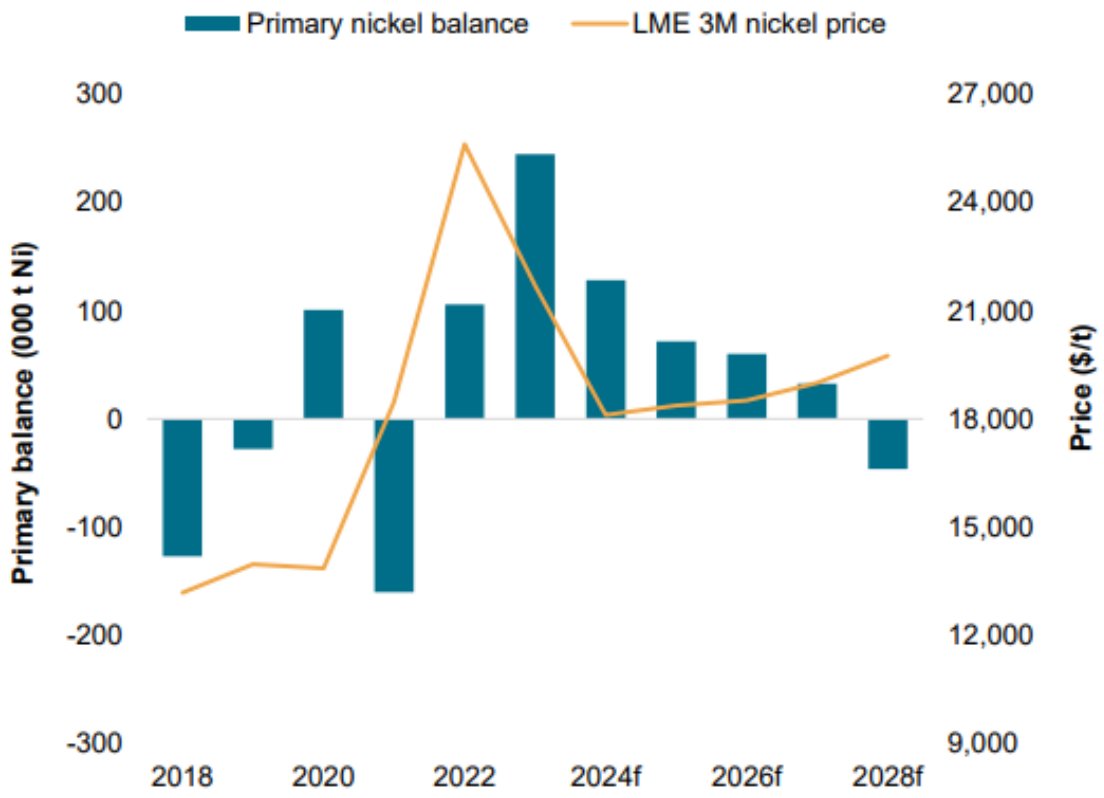
2023-2024 is proving challenging for high cost nickel producers



Source: LME and S&P

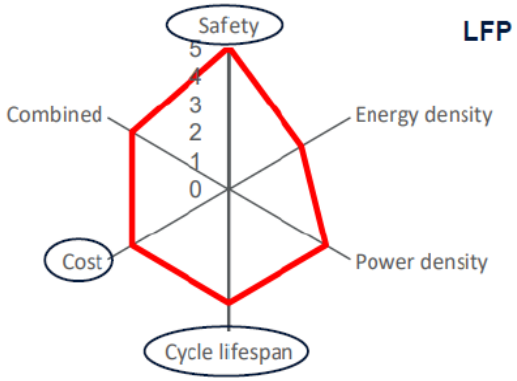
Industry analysts predict supply will exceed demand until 2028+

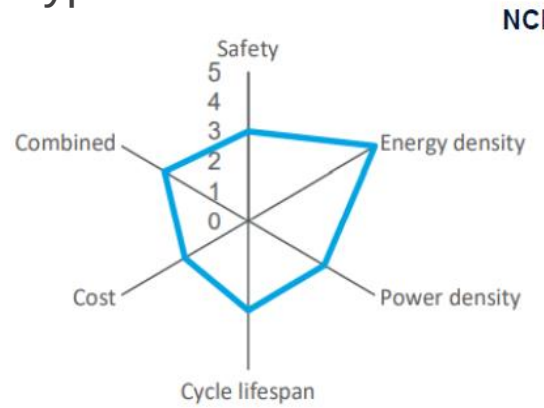
Global primary nickel market to remain oversupplied in 2024

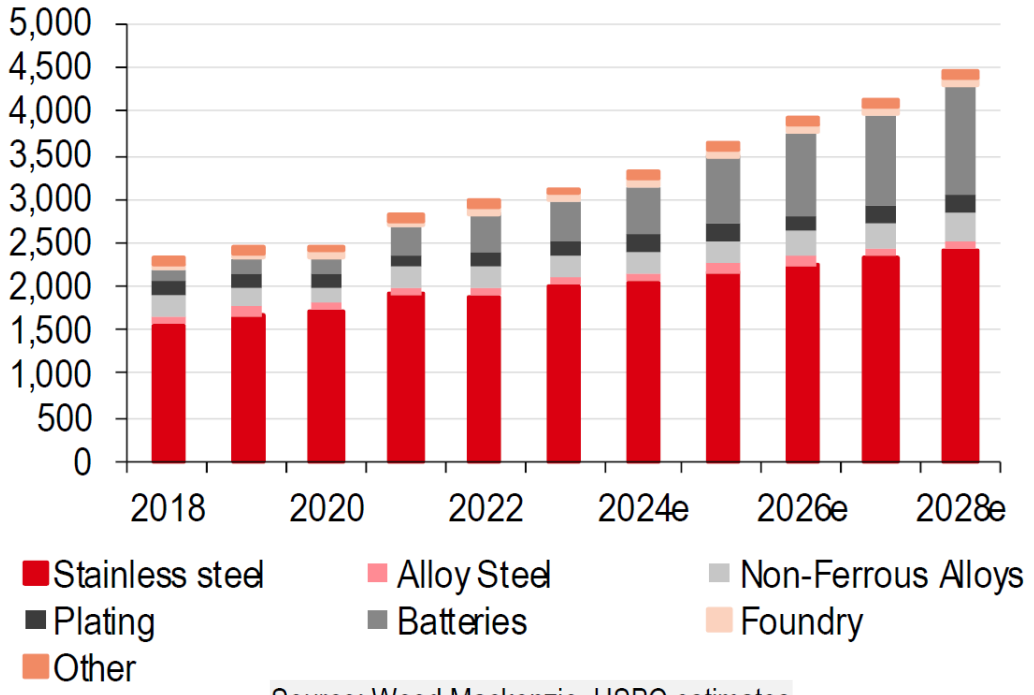


Source: S&P

Battery Types







Source: Wood Mackenzie, HSBC estimates

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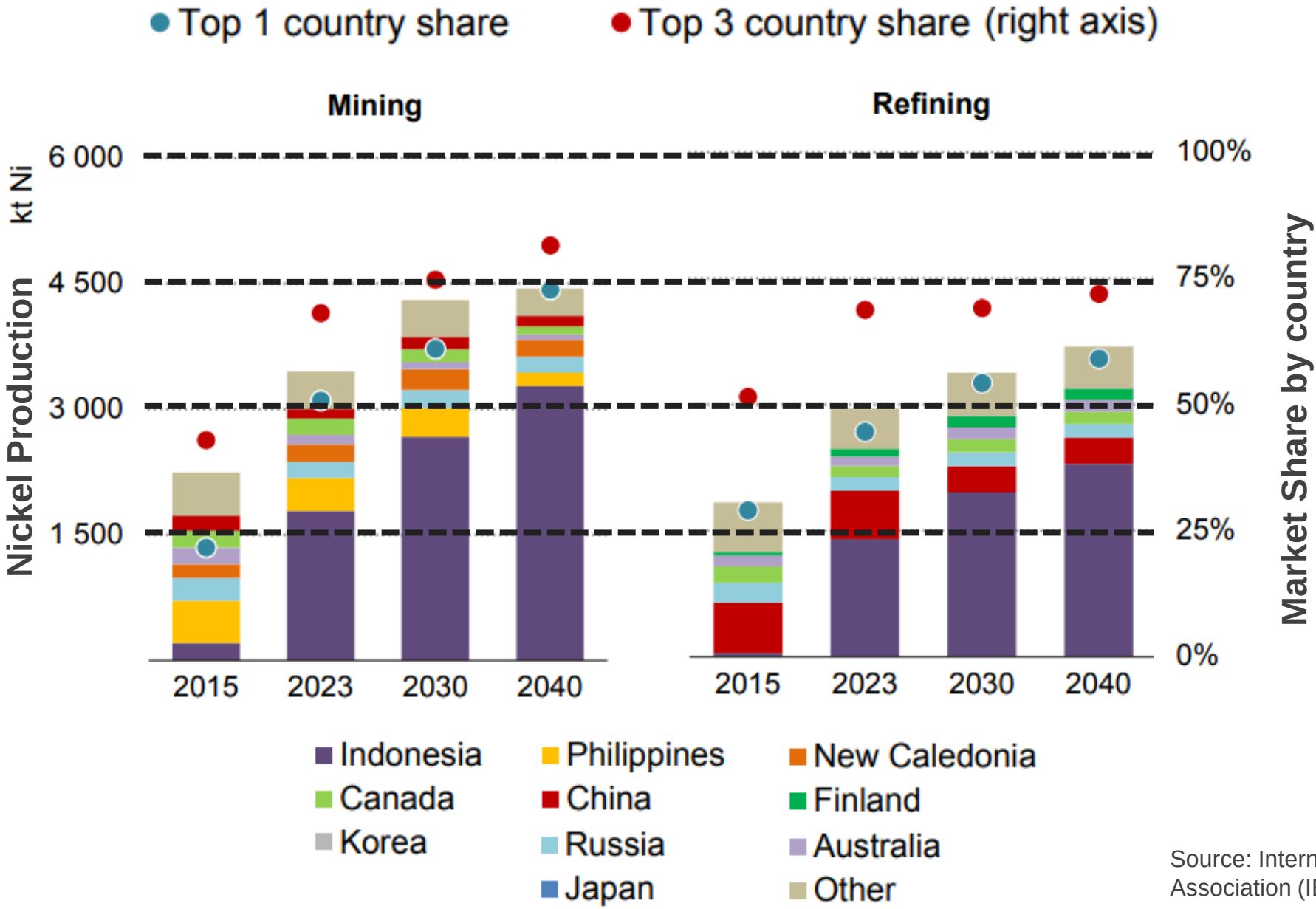
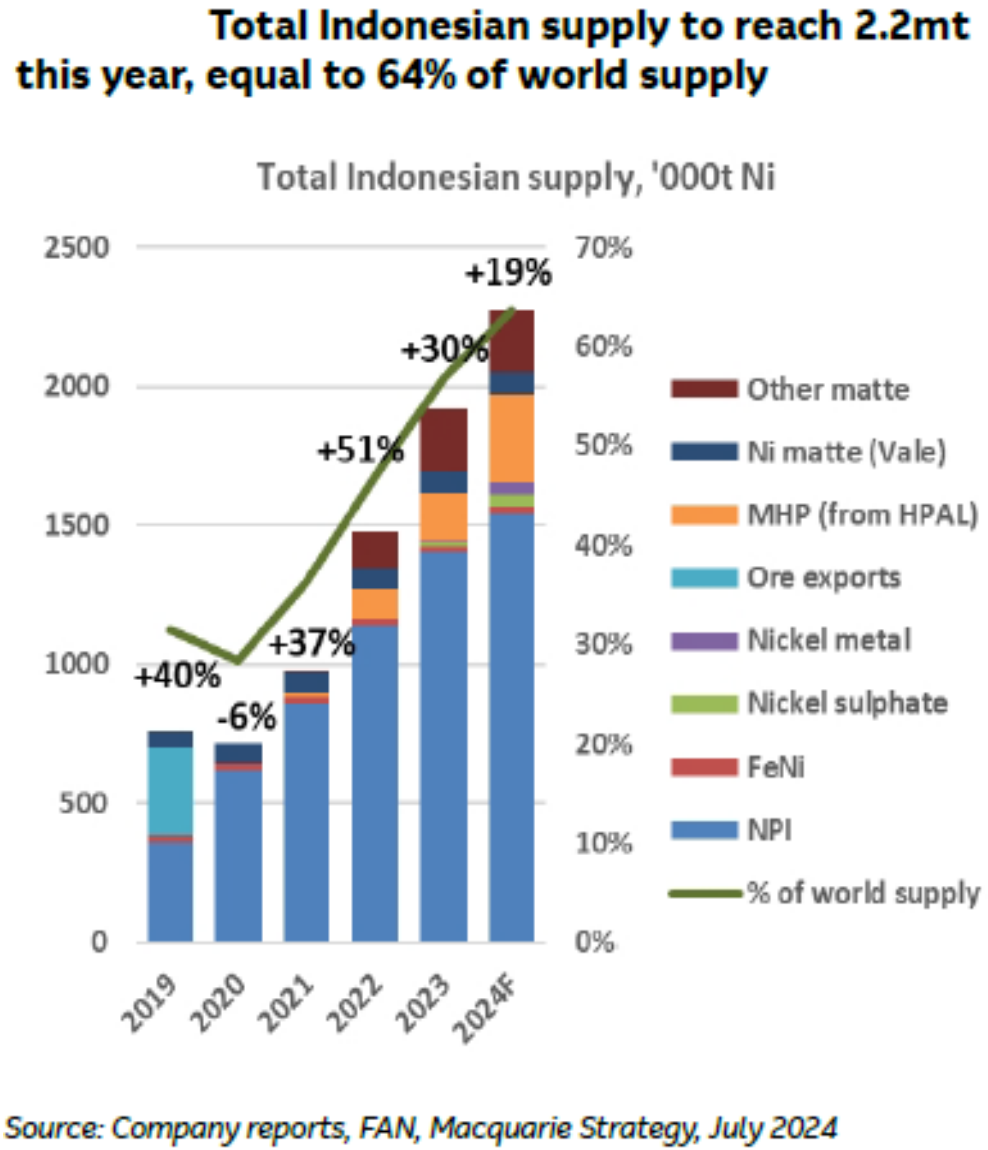
Indonesia – dominating nickel mining and refining



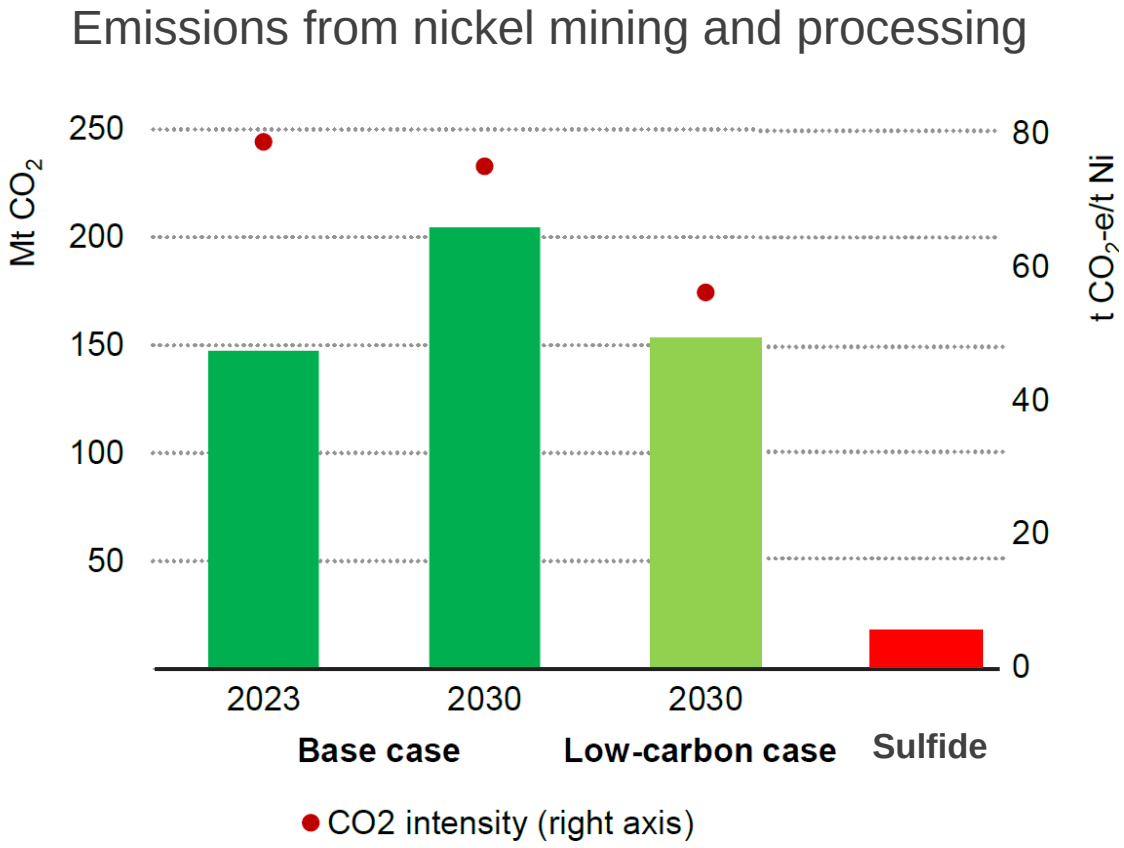
Source: International Energy Association (IEA) 2024

Indonesia – Growth mostly in NPI and HPAL



Source: Company reports, FAN, Macquarie Strategy, July 2024

CO_2 emissions from laterites ~5-10x sulfides



Source: IEA 2024, CRU 2023, Trytten 2022

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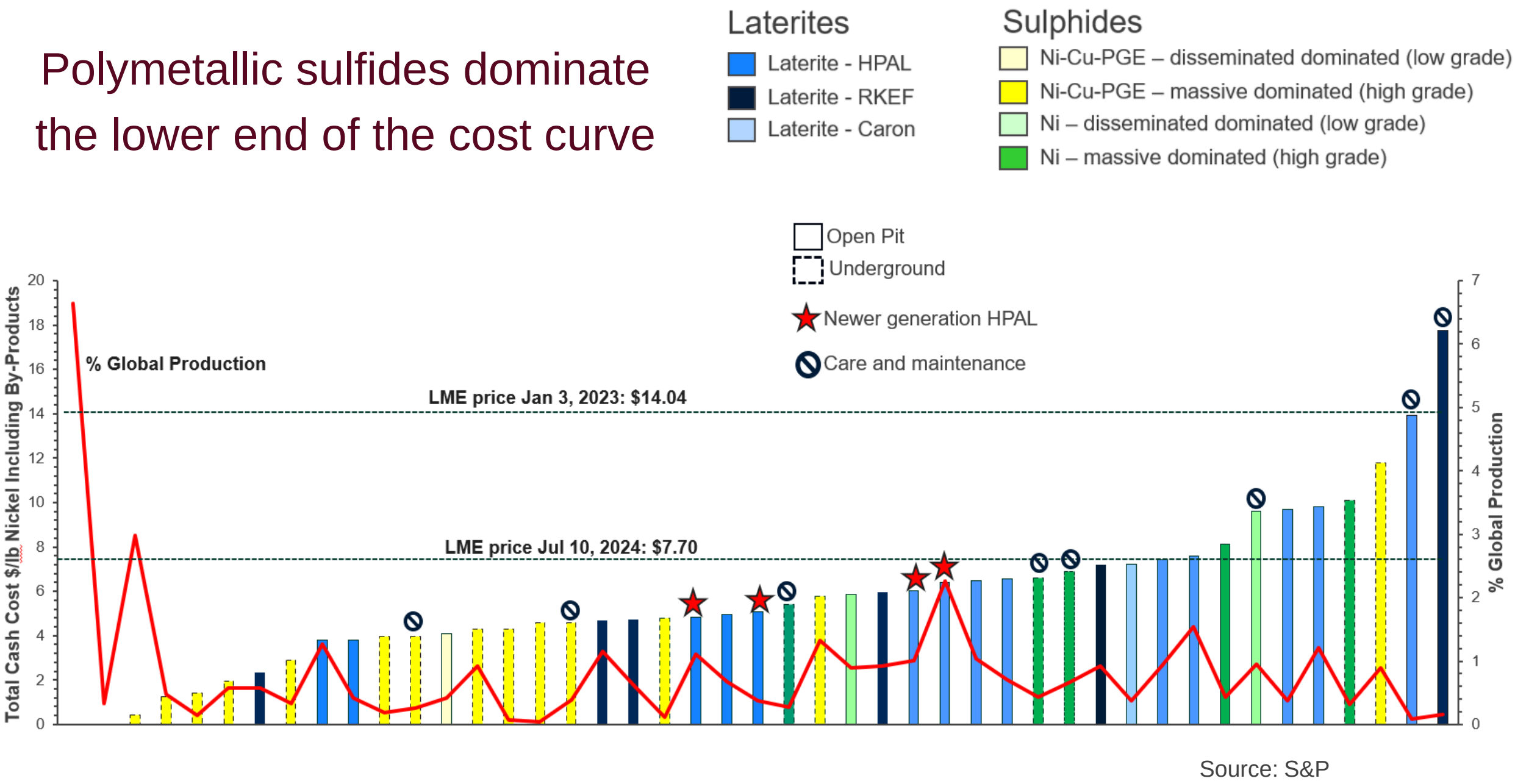
Polymetallic sulfides dominate the lower end of the cost curve



Source: S&P

HPAL = high pressure acid leach
RKEF = rotary kiln electric furnace

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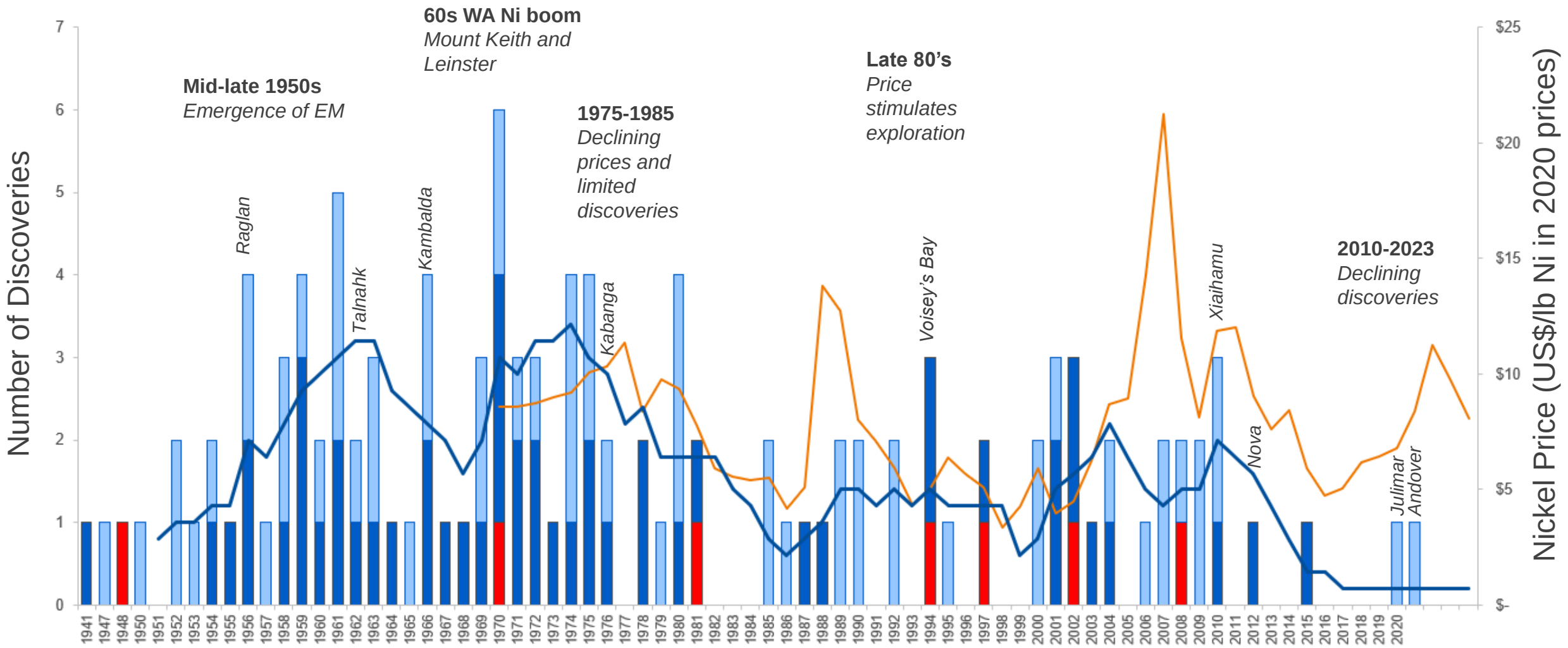
Significant nickel sulfide discoveries continue to decline



Source: MinEx Consulting and RTX

Problem statement

Ni market is oversupplied with less environmentally-friendly lateritic Ni with mining and processing largely dependent on two countries (Indonesia and China).

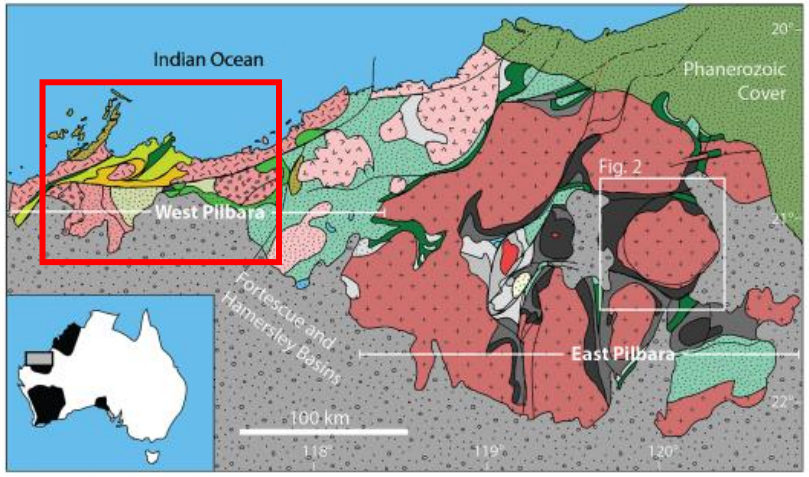
a) Most Ni laterite mining and processing operations have a significant environmental impact with increased CO_2 emissions and significantly larger footprints (land use area). Sulfides are more sustainable than current laterite mining and processing practices.

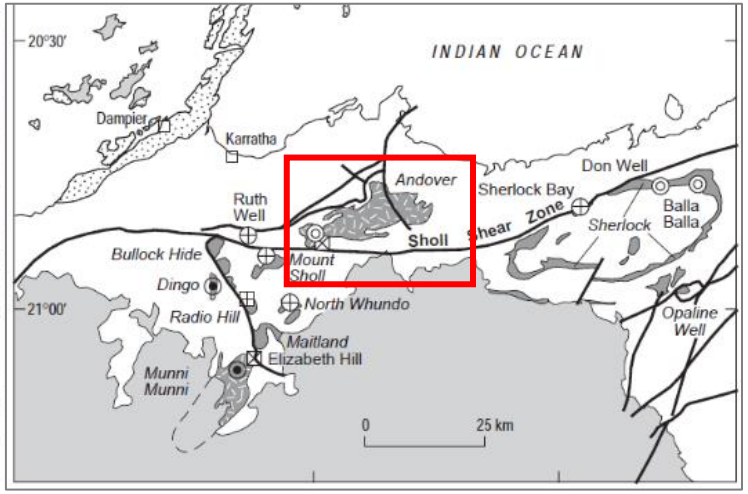
b) In 2023, 54% of Ni mining supply came from Indonesia and 71% of processing came from Indonesia and China.

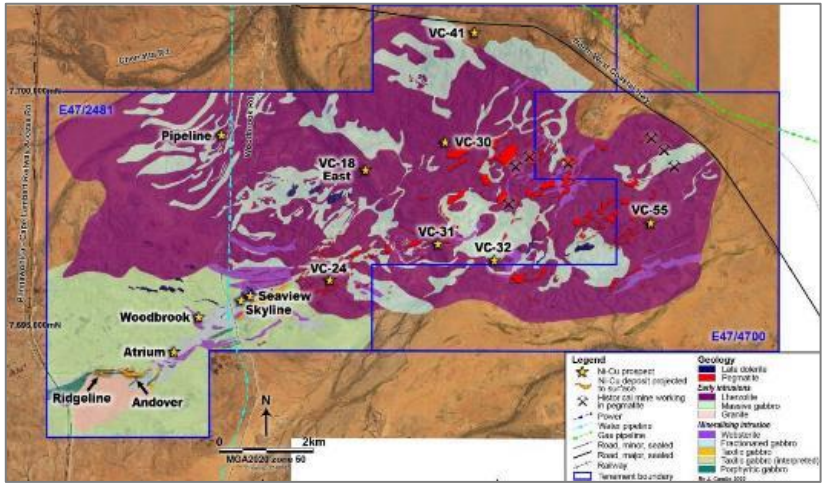
c) And…after all polymetallic Ni sulphides are cheaper to produce!

Exploration stages

1. Craton/Terrain Scale – Generative Stage
2. Camp Scale – Generative Stage
3. Project Scale – Project Stage







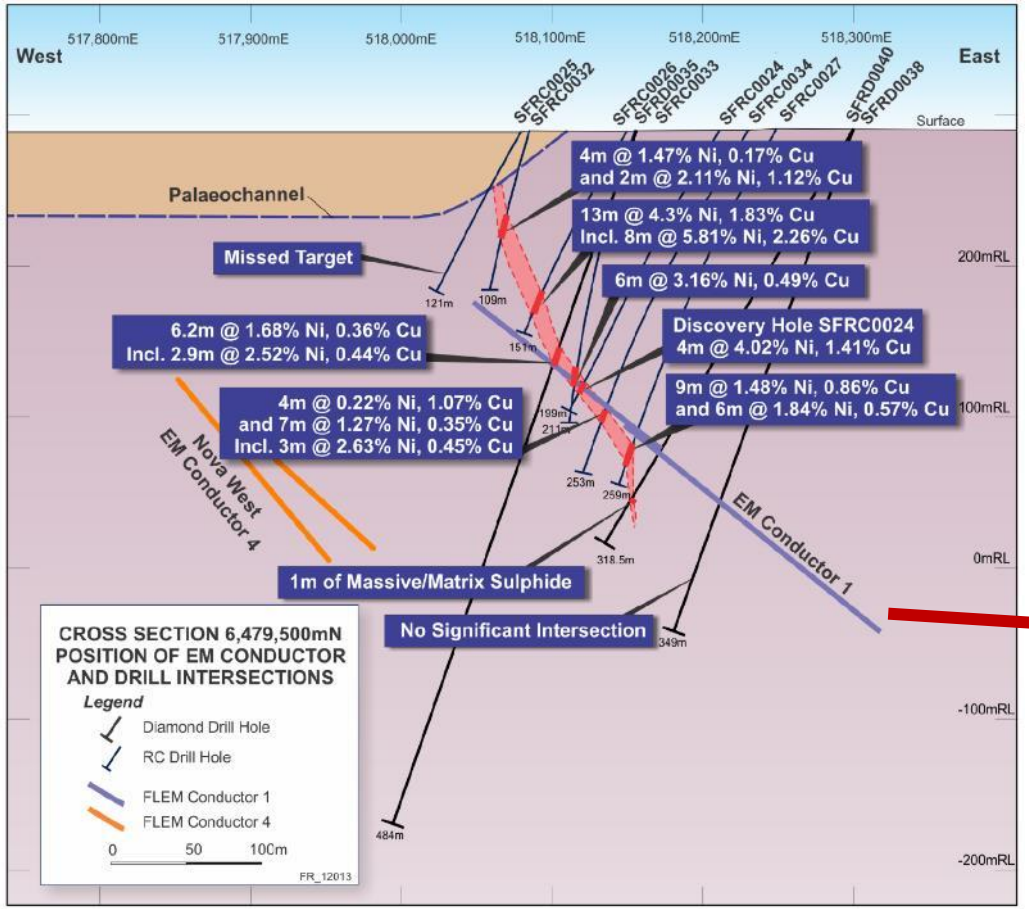
An example – The Pilbara Craton

West Pilbara

Andover

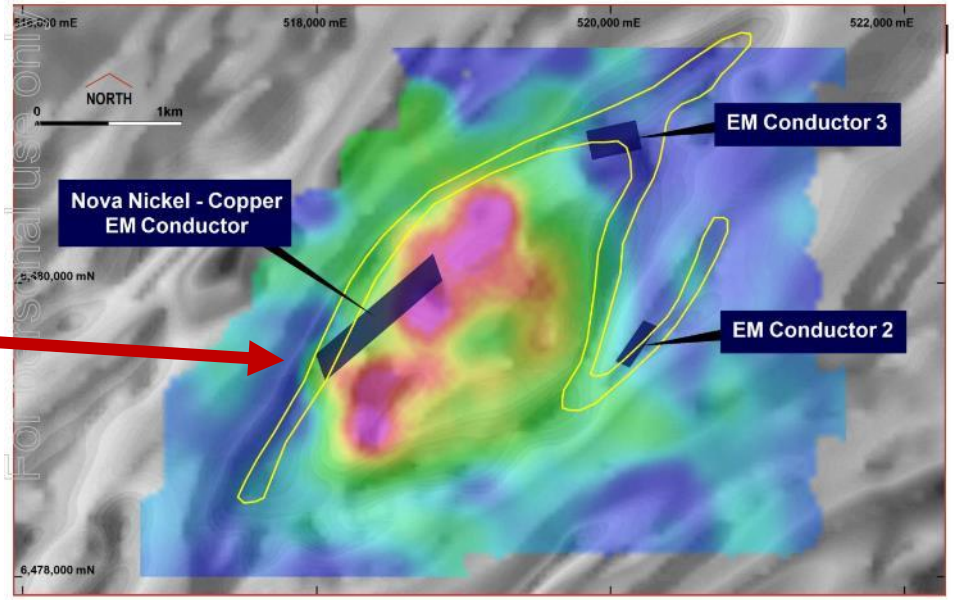
What are NiS explorationists good at?

Nova-Bollinger Discovery



- Exploration at the deposit (small) scale, in particular, direct detection of conductive sulfides by geophysics
- AEM + ground EM, and borehole EM

DEPOSIT SCALE



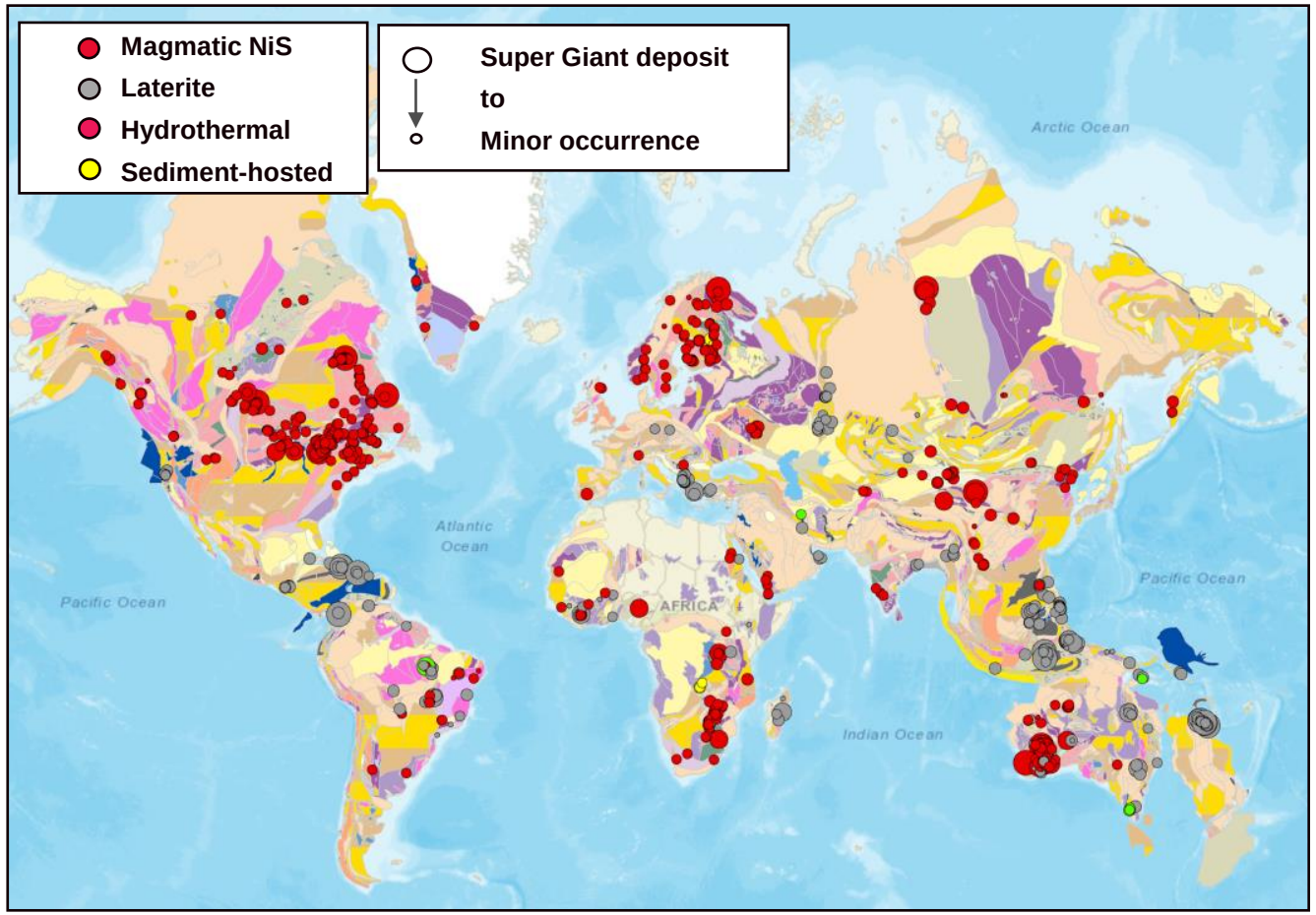
Source: Sirius Resources October 2012

Discovery Techniques – Quick Overview

Deposit Type	Cover Type	TARGET TESTING SCALE		
		Geophysics	Geochemistry	Prospecting/ Reconnaissance
Massive sulfide dominated deposit	Thin cover	EM (airborne, ground, borehole) Magnetics and/or gravity	Surface geochemistry effective at tight spacing	Gossans, surface grabs with anomalous Ni, Cu, PGE – potentially subtle
	Thick cover		Surface geochemistry ineffective	Mostly ineffective
Disseminated sulfide dominated deposit	Thin cover	Magnetics and/or gravity (Induced polarization)	Surface geochemistry very effective due to large footprint	Gossans, surface grabs with anomalous Ni, Cu, PGE – potentially subtle
	Thick cover		Surface geochemistry ineffective	Mostly ineffective

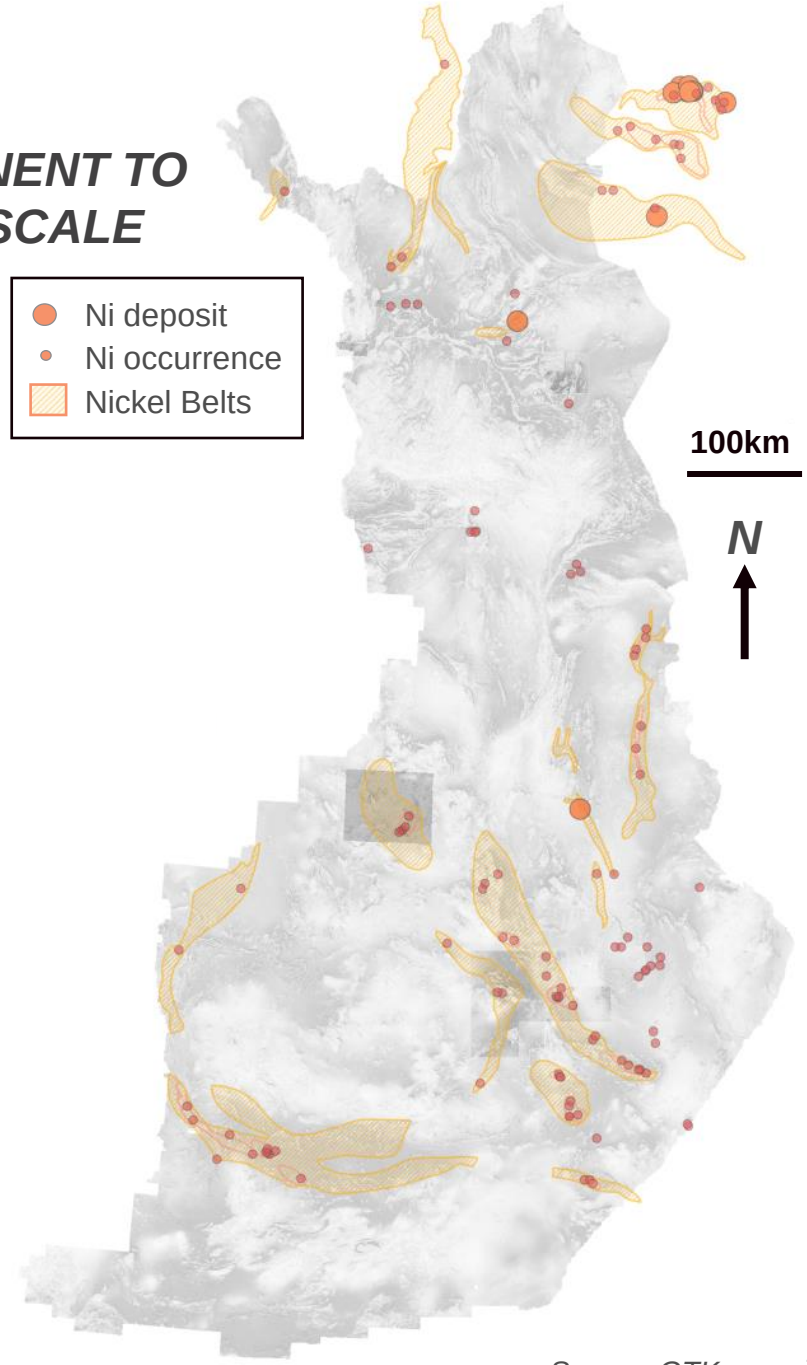
What are we not so good at?

- Identifying favorable terranes and camps
- Particularly when moving into new areas (away from known deposits or extensions of known belts)



Source: MinEx Consulting and RTX

CONTINENT TO CAMP SCALE

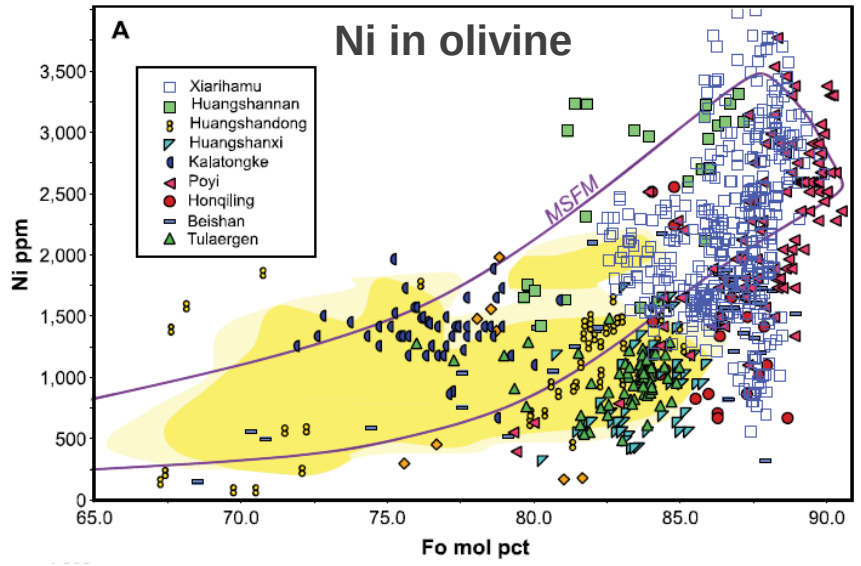


Source: GTK

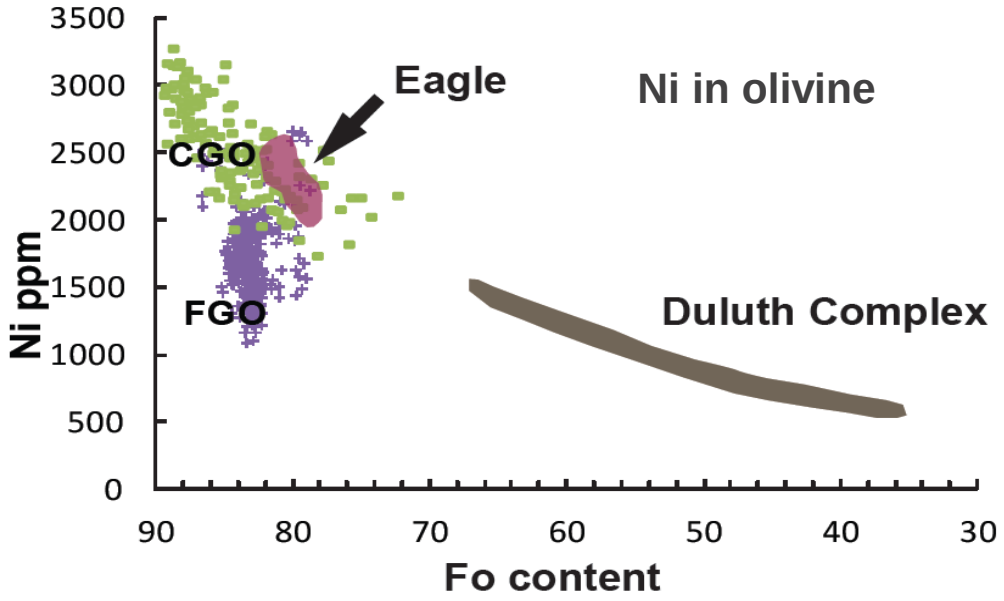
What are we not so good at?

- Recognizing fertile intrusions
- Many false positives and negatives from:
  - Mineral chemistry
  - Whole rock data
  - Surficial chemistry
  - False EM conductors – graphitic sediments

CAMP TO DEPOSIT SCALE



Source: Barnes et al. 2023



What are we not so good at?

Knowing what we are looking for….

- Focus on high grade massive sulfides but…
  - ➢ The economics of such deposits are not always favorable
  - ➢ Massive sulfide deposits are more difficult exploration targets compared to large disseminated Ni deposits
    - Smaller footprints
    - More drill intensive
    - Often incremental resource growth

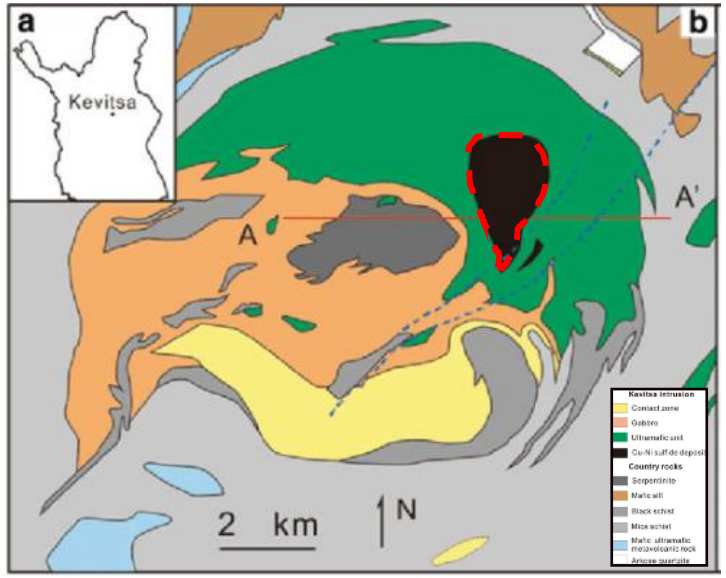
Mineralization footprint projected to surface

All same scale

CAMP TO DEPOSIT SCALE

Kevitsa

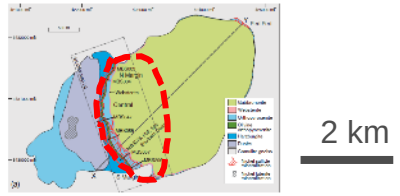
Olivine Pyroxenite-hosted



Discovery: Weakly mineralized surface boulders + strong base of till anomaly

Source: Yang et al., 2013

Santa Rita Deposit



Discovery: Stream + soil (Ni, Cu, Co) + IP

Pyroxenite-Peridotite-hosted

Source: Barnes et al. 2011

Exploration stages – what are we using from research (either academia or industry-driven)

1. Craton/Terrain Scale – Generative Stage

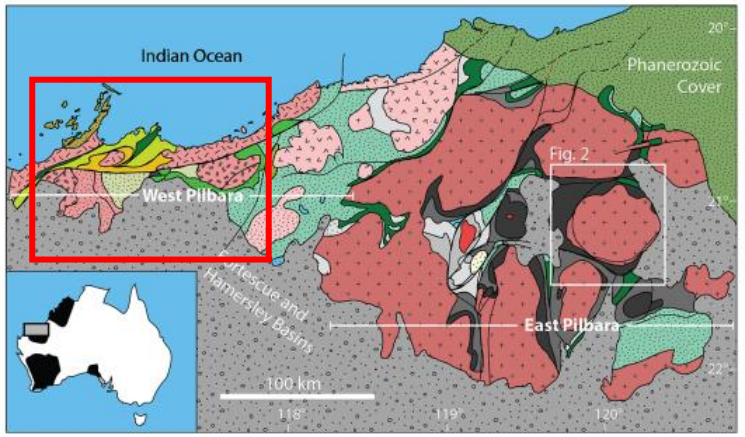
- Lithospheric Architecture Maps (GLAMS), Domain Boundaries + Trans-lithospheric structures
- Paleogeographic reconstructions – what were formerly connected? Form of near-ism)
- LIP research

2. Camp Scale – Generative Stage

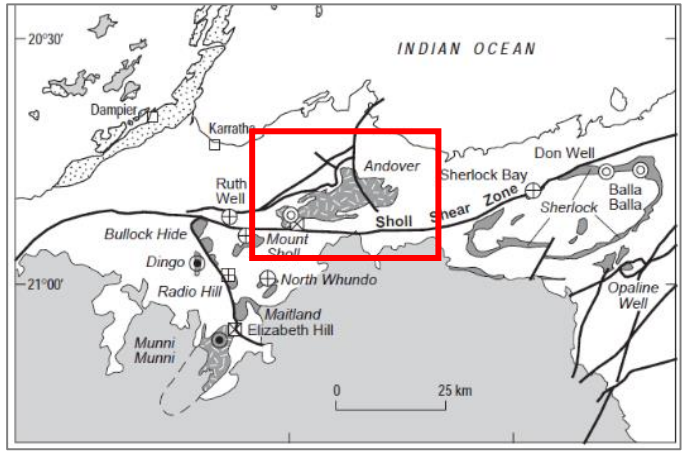
- Major Structures
- Identification of Mafic-Ultramafic Intrusions (mag, geochemistry, surficial geochemistry)
- Empirical/Direct Detections Surficial Geochemistry (soils, streams, till, RIMs)
- Fertility Indicators – mineral chemistry, whole rock
- Favorable country rocks (S-source, reactive rocks [oxygen fugacity])

3. Project Scale – Project Stage

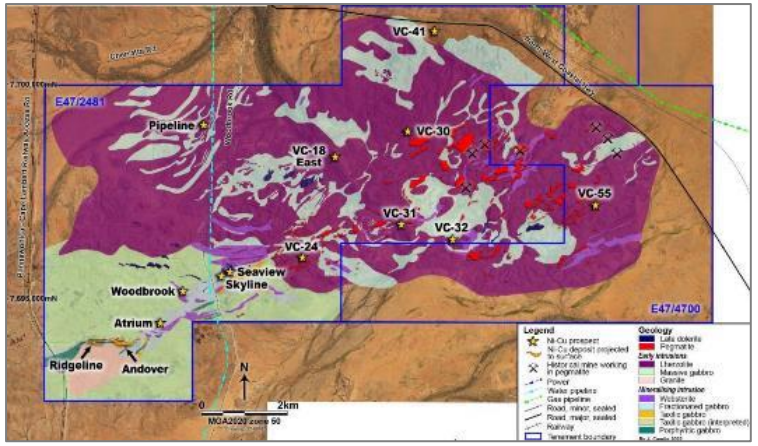
- Fertility indicators – mineral chemistry, whole rock
- Favorable country rocks (S-source, reactive rocks [oxygen fugacity])
- Indicators of processes including S. saturation, types of contaminants (δS34)



An example – The Pilbara Craton



West Pilbara



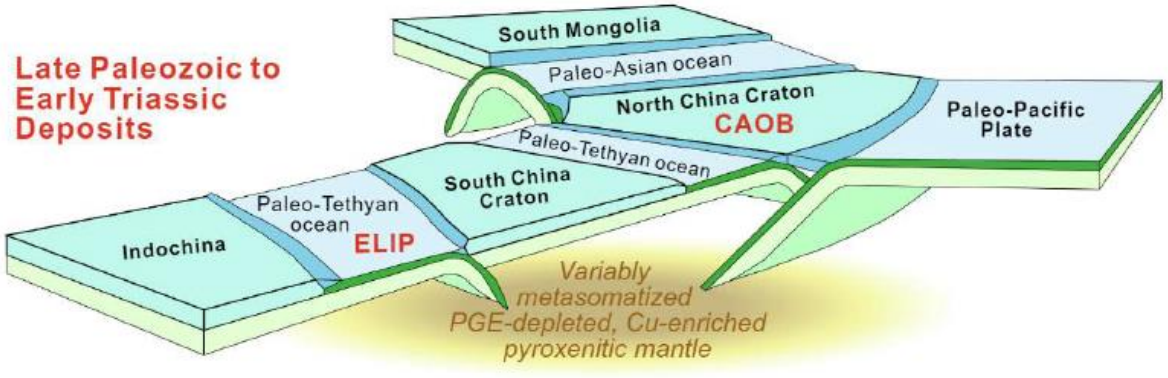
Andover

We have a credible understanding of nickel sulfide systems at the deposit scale….but…

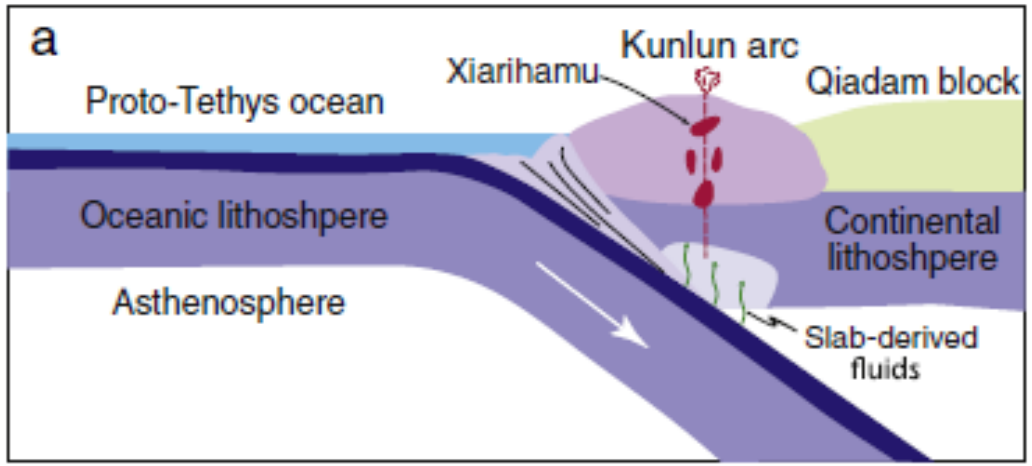
- But we are not discovering sufficient high-quality NiS deposits in a timely manner
- Most of our discoveries are serendipity or from surface gossans and/or surface mineralization
- Ni deposits are generally drill intensive and we struggle to identify those deposits which require further persistence

What are (industry and academia) stuck on

- The assumption that many nickel-mineralized ultramafic-mafic intrusions are sourced from mantle-derived plumes
- Many exceptions including Nova-Bollinger and the abundant Central Asian Orogenic Belt intrusions
- What is the evidence that the host ultramafic-mafic intrusions for many nickel deposits are plume-derived?



Source: Lu et al., 2019

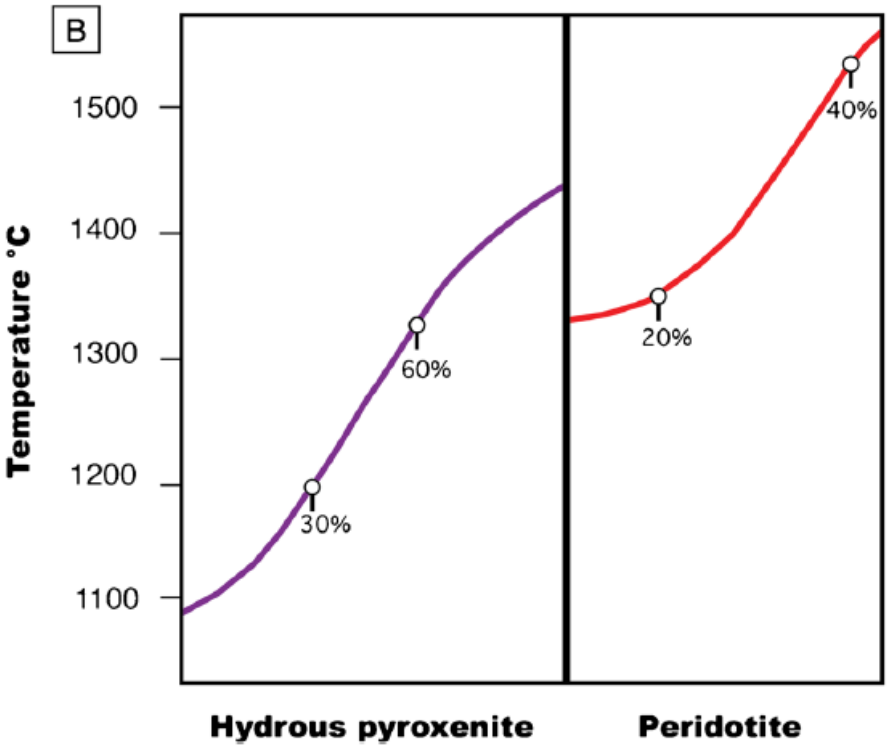


Source: Zhang et al. 2015

CONTINENTAL TO CAMP SCALE

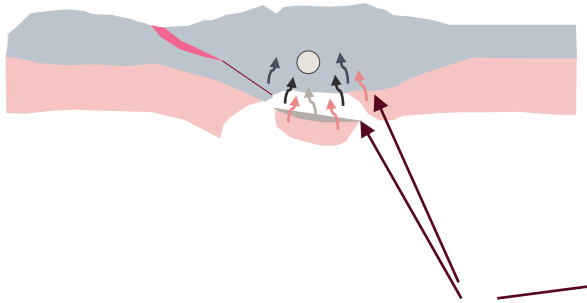
Howell, Blanks and Ezad + team – lithospheric hydrous pyroxenitic mantle – control by hydrous minerals

- Ni can be present in metasomatized mantle (hydrous pyroxenites) ir amphiboles (up to 1500 ppm Ni) + phlogopite (up to 6000 ppm Ni)
- Lower melting temperatures to extract Ni into the melt

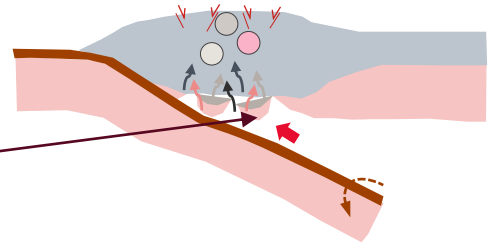


Source: Ezad et al., 2024

Collisional orogens



Accretionary orogens



Fertile Ni-bearing melts sourced from pyroxenitic cumulates metasomatized lithospheric mantle

Source mantle

- Development of pyroxenitic domains in the lithosphere, mantle and/or lower crust
- Melting (~1100 °C) with heat from orogen-related processes

Heat

- Slab-break-off
- Slab-roll back
- Delamination dense pyroxenite cumulates (arclogites) in accretionary orogenic growth

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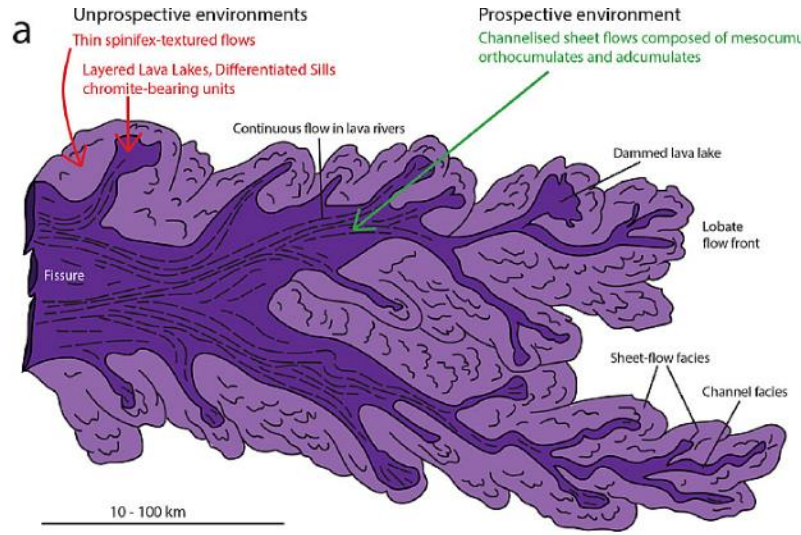
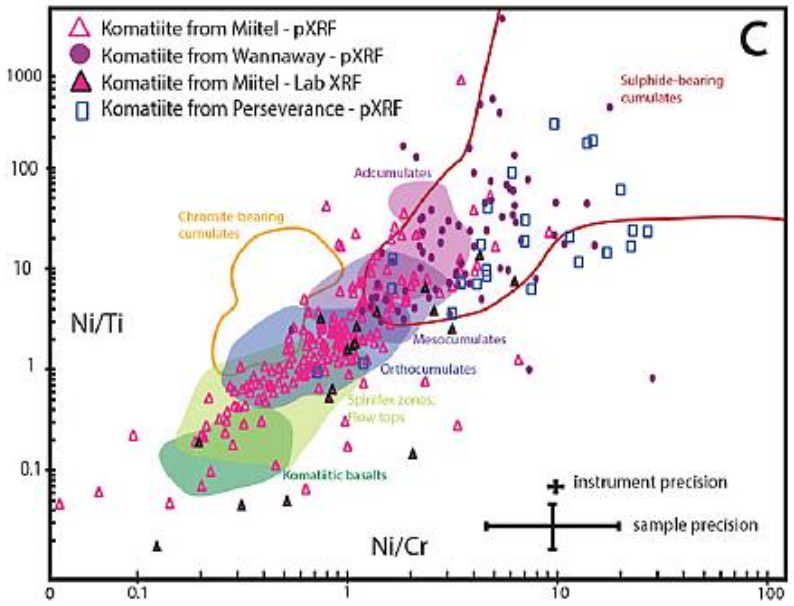
What are (industry and academia) stuck on

- Over-emphasizing the application of knowledge from komatiitic nickel systems to high Mg and tholeiitic systems
  - ➢ Emplacement methods + crustal levels – shallow to subaerial
  - ➢ Physical processes (rheology, viscosity differences etc) – magma transport, eruption
  - ➢ Thermodynamic understandings – assimilation etc
  - ➢ Mineralization processes
  - ➢ Sulfide migration and accumulation – wetting angles
  - ➢ Exploration methodologies and fertility indicators (e.g., Ni/Cr, Ni/Ti ratios)



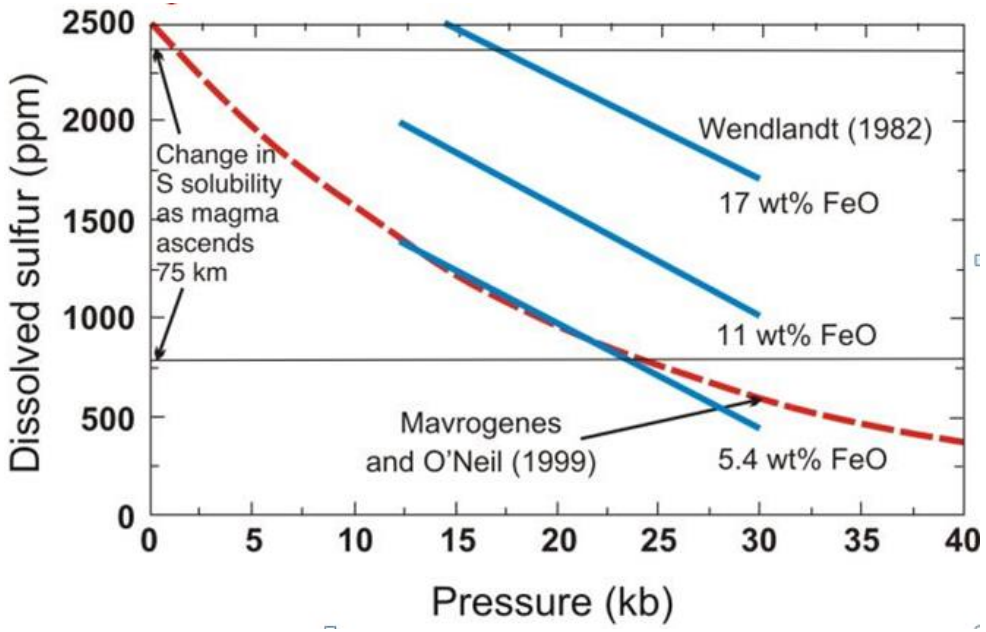


CONTINENTAL TO CAMP SCALE

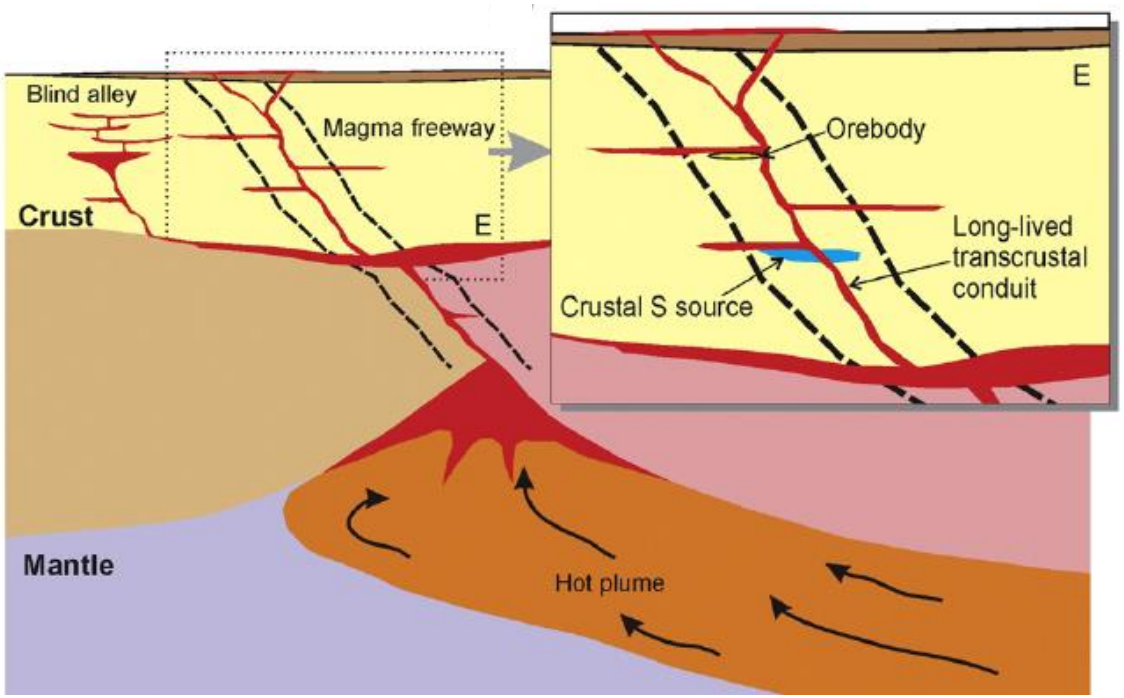
Source: Le Vaillant et al., 2016

What are (industry and academia) stuck on

- Treating intrusions from different crustal levels in the same way
- We need to distinguish shallow/subaerial ultramafic-mafic hosted systems from those intrusions that crystallize at greater depth in the mid crust
  - ➢ The mechanisms for S-saturation may be different
  - ➢ Inverse relationship between S-solubility and pressure
  - ➢ Conduit formation processes may be different
  - ➢ Timescales are different (Barnes et al., 2021)

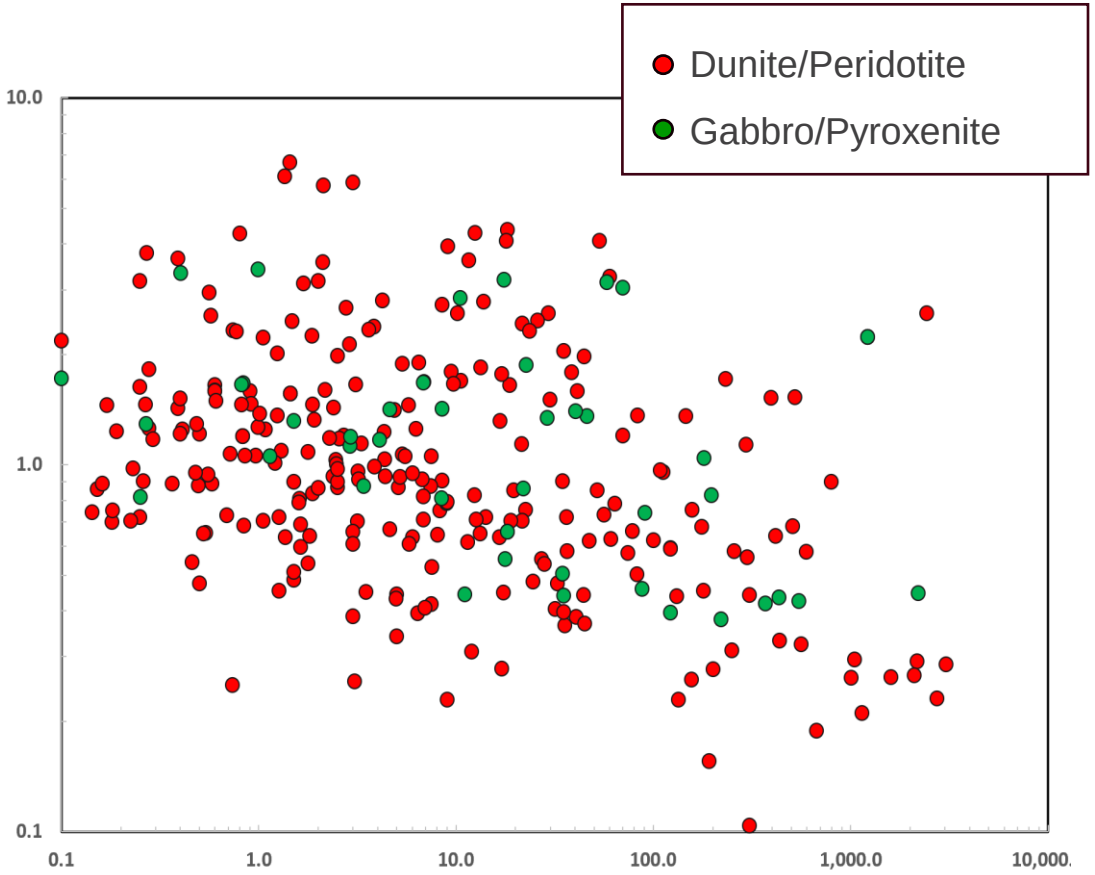


CONTINENTAL TO CAMP TO DEPOSIT SCALE



What are (industry and academia) stuck on

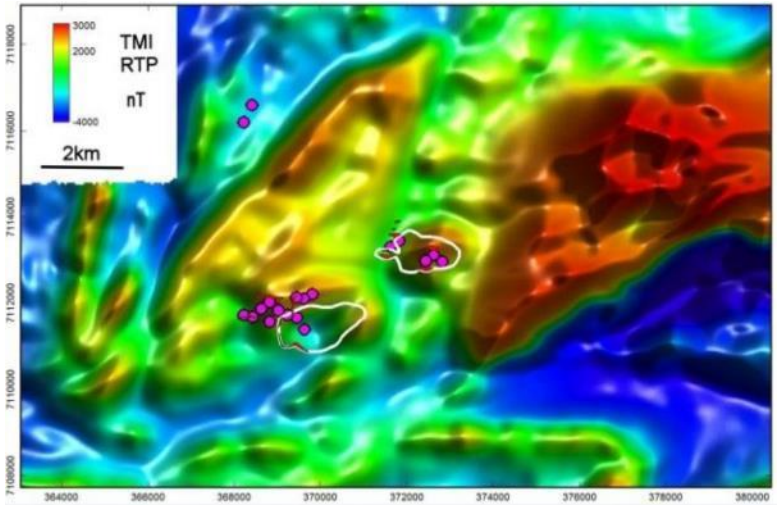
- Over-emphasis on intrusions dominated by olivine (peridotites, dunites) versus pyroxene and plagioclase (pyroxenites, gabbro (norites)
- Abundant mineralization associated with pyroxenitic and gabbroic systems
- Largely under recognized in magnetics (dominant mapping tool in industry)



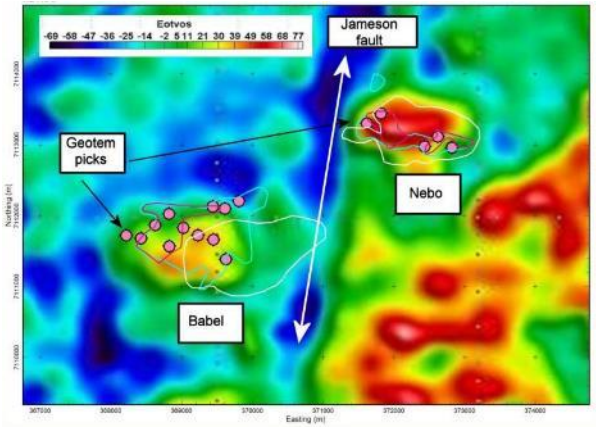
Source: MinEx Consulting and RTX

50m mag

Nebo Babel



Airborne gravity (Falcon)



CAMP TO DEPOSIT SCALE

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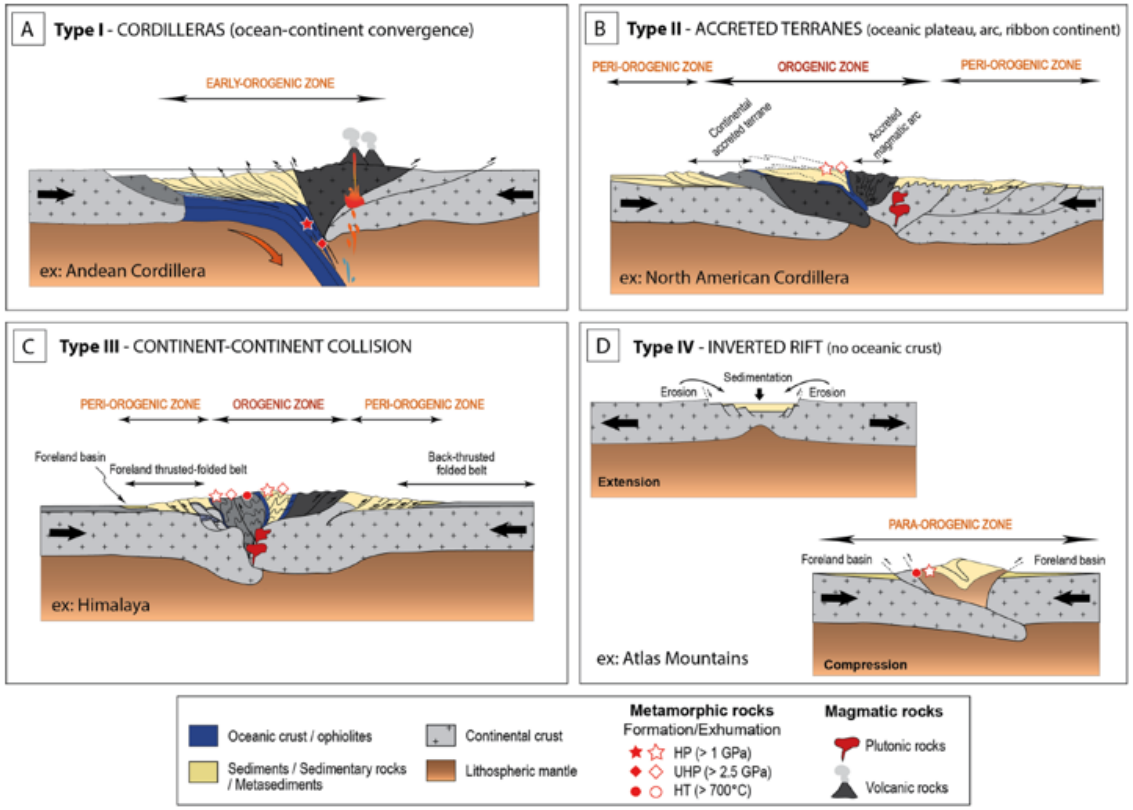
Source: Witherly and Sattel, 2018

What do researchers need to understand better?

CONTINENTAL SCALE

- Improved understanding of mantle fertility + lithospheric source regions
- Pyroxenitic versus peridotitic mantle, timing of enrichment, scale of enrichment
- Detailed age dating and linkage of host intrusions and mineralization within the orogenic cycle

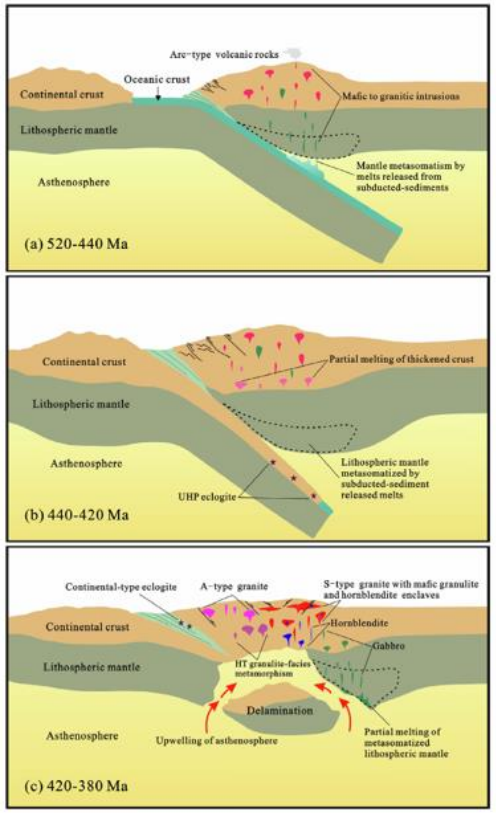


Source: Francois et al., 2021
(IGCP 667 project: World Map of orogens)

Pre-collision (subduction)

Syn-collision

Post-collision (delamination +/- slab-break off)

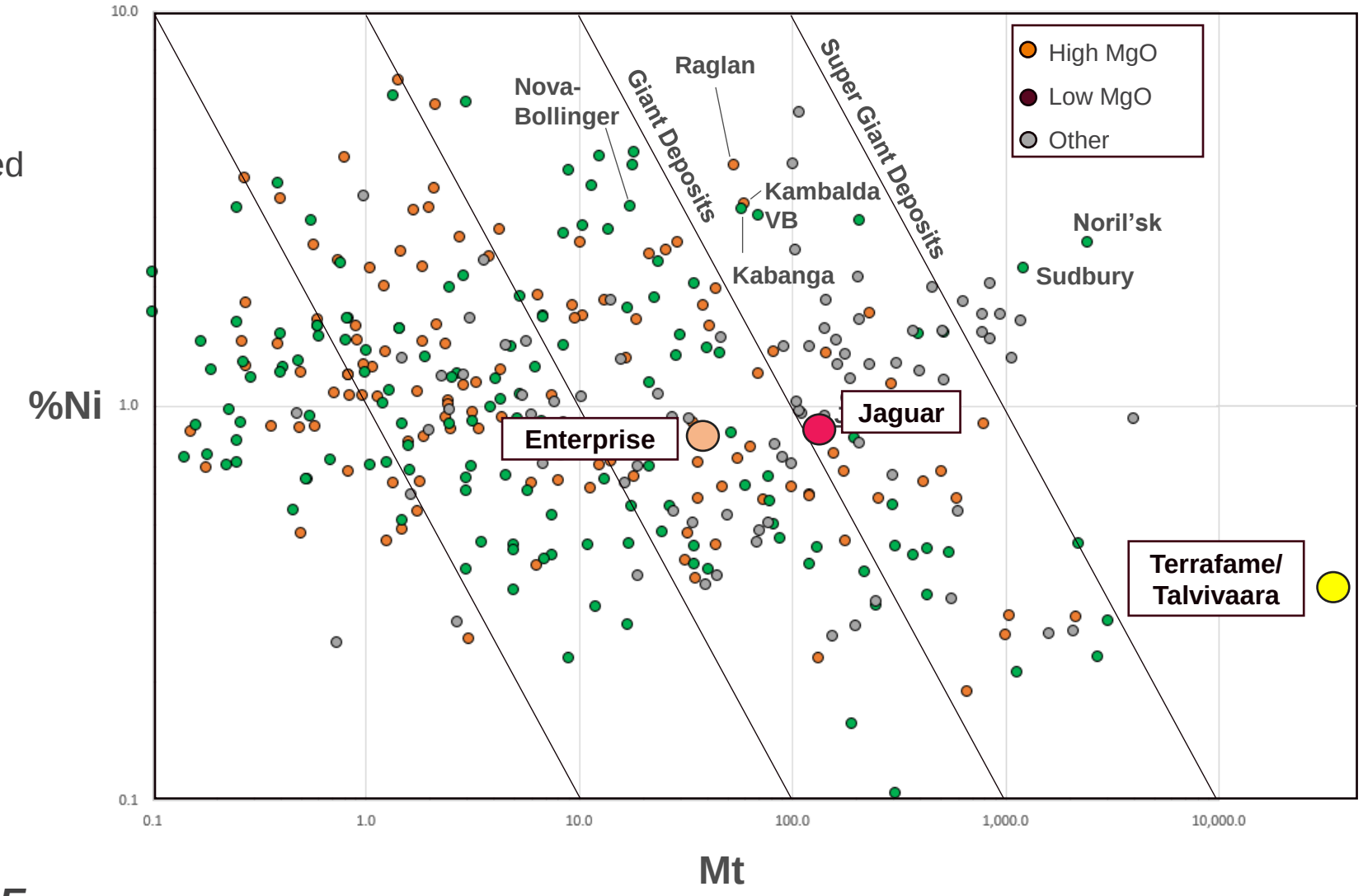


***Example**: East Kunlun Orogenic Belt, from Wang et al., 2022 (GF)*

What do industry need to understand better?

Unconventional Ni deposits:

- Overemphasis on sulfide-associated mafic-ultramafic intrusives – what about other deposits including:
  - ➢ Hydrothermal Ni deposits:
    - – Jaguar – the next >1Moz Ni deposit
  - ➢ Sediment-hosted Ni deposits
    - – Enterprise
    - – Talvivaara/Terrafame



DEPOSIT SCALE

Source: MinEx Consulting

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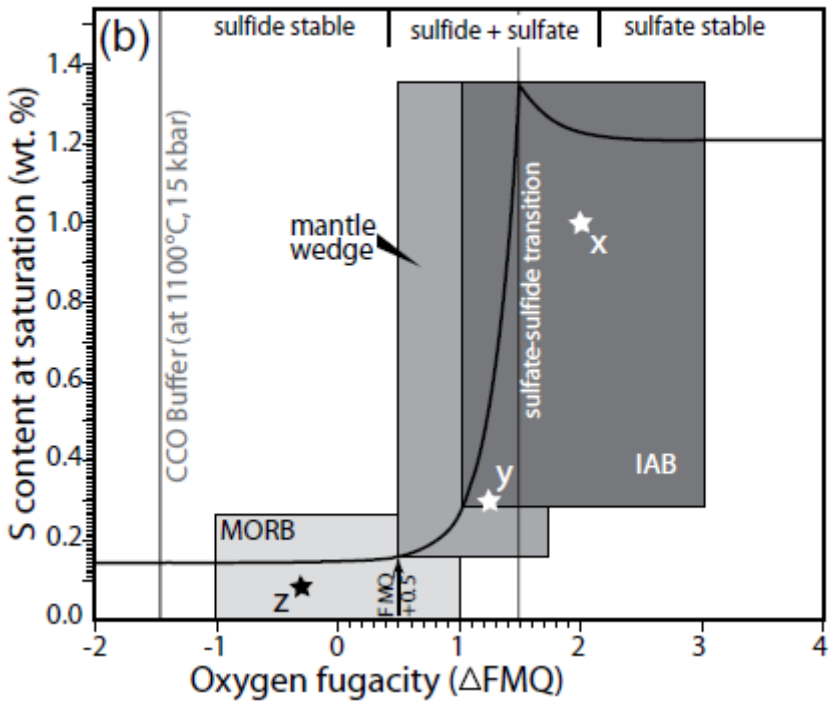
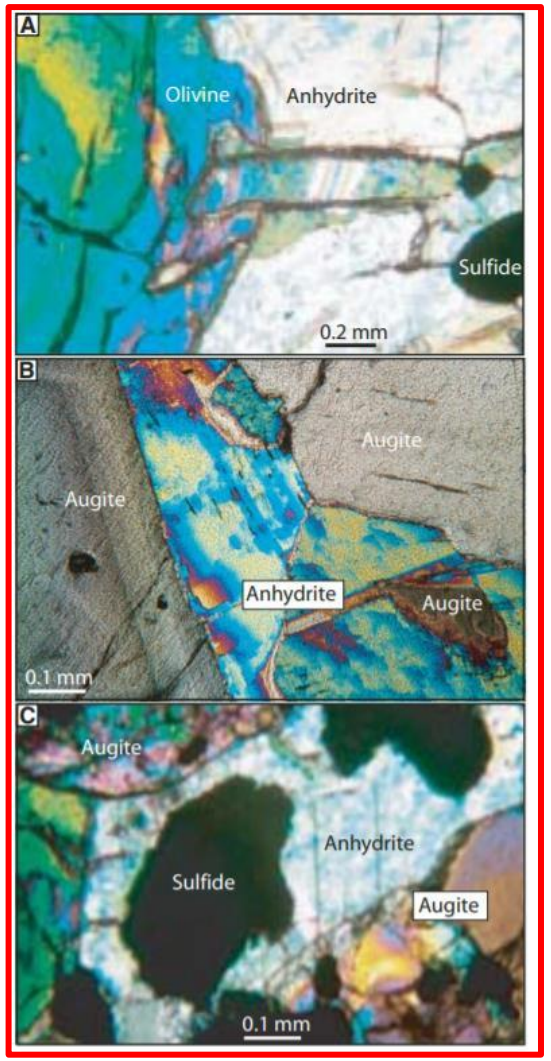
What do researchers need to understand better?

Improved understanding of the relative roles of different types of country rocks as (a) sources of sulfur (sulfide/sulfate) and (b) triggers for sulfur saturation including redox changes



Norilsk – Devonian evaporites

Norilsk- Permian coal



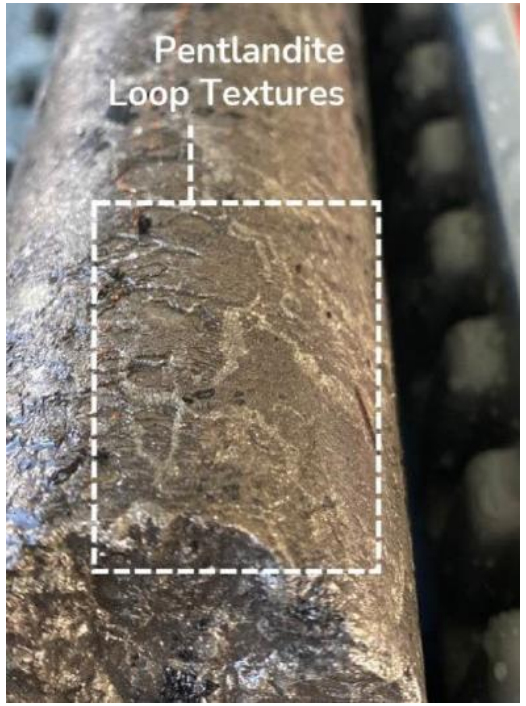
What do researchers need to understand better?

Processes for massive sulfide accumulation at variable crustal levels in the crust

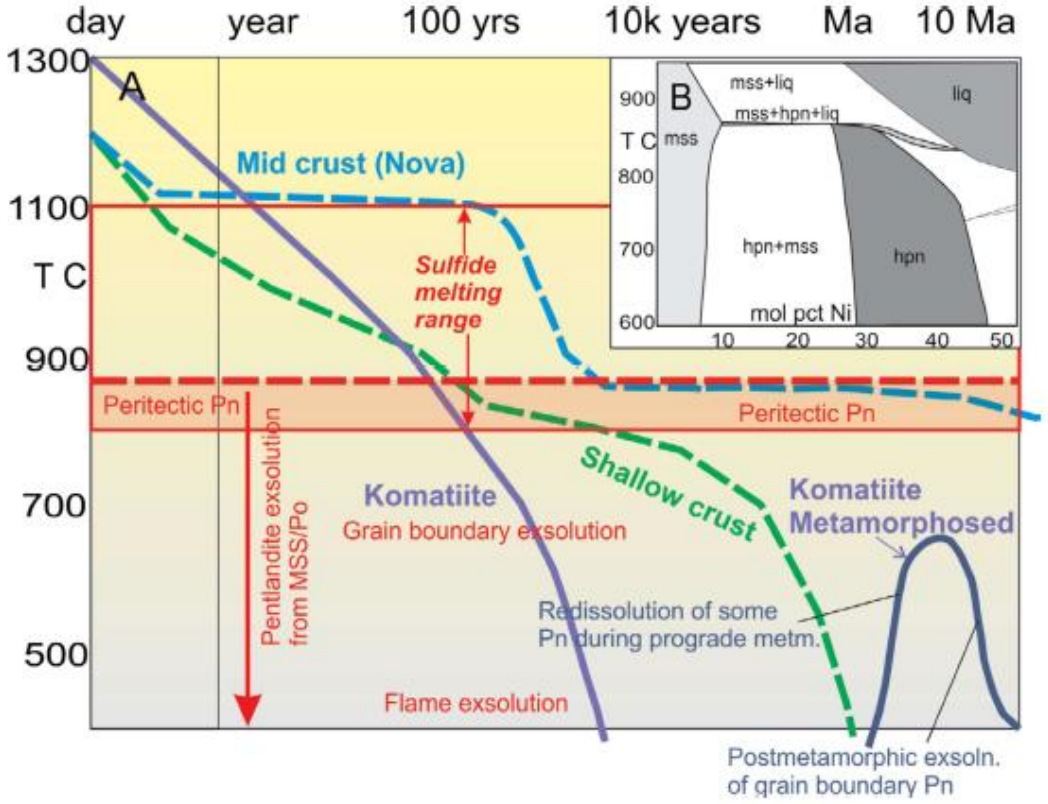
DEPOSIT SCALE

Curaçá Valley, Brazil

Source: Ero Copper, 2023



Timescale + Temperature paths for pentlandite



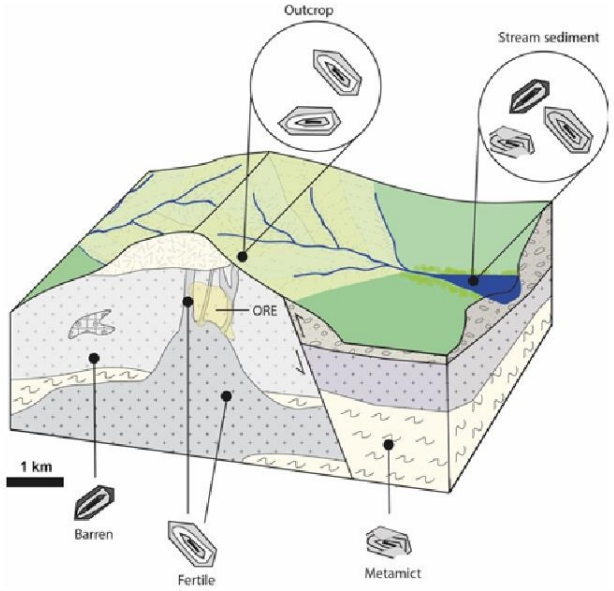
Source: Barnes et al., 2020

What do industry need?

Improved Footprint Studies on Nickel Ore Deposits and their Host Intrusions in 3D

- Geophysics
  - ➢ Gravity, magnetics, EM
- Geochemistry
  - ➢ Whole rock and mineral chemistry (particularly trace element with MLA)
  - ➢ Surficial chemistry
- Geology

DEPOSIT SCALE



Source: Cooke et al. 2020

Porphyry Copper Footprints

Nickel Sulfides

Range Parental magma types

Range Crustal Depths

Range Tectonic Settings

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What do industry really need to be more successful explorers

- New nickel search spaces
- Improved understanding that crustal level plays in Ni sulfide ore forming processes
- Improved understanding of parental magma composition
- Improved understanding of the importance of country rocks
- Better understanding of unconventional Ni deposits
- Better understanding of deposit footprints

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