The record of flood basalt magmatism in Siberia, and origin of the Ni-Cu-PGE sulfide ores at Noril'sk-Talnakh

Peter C. Lightfoot, Vale Base Metals

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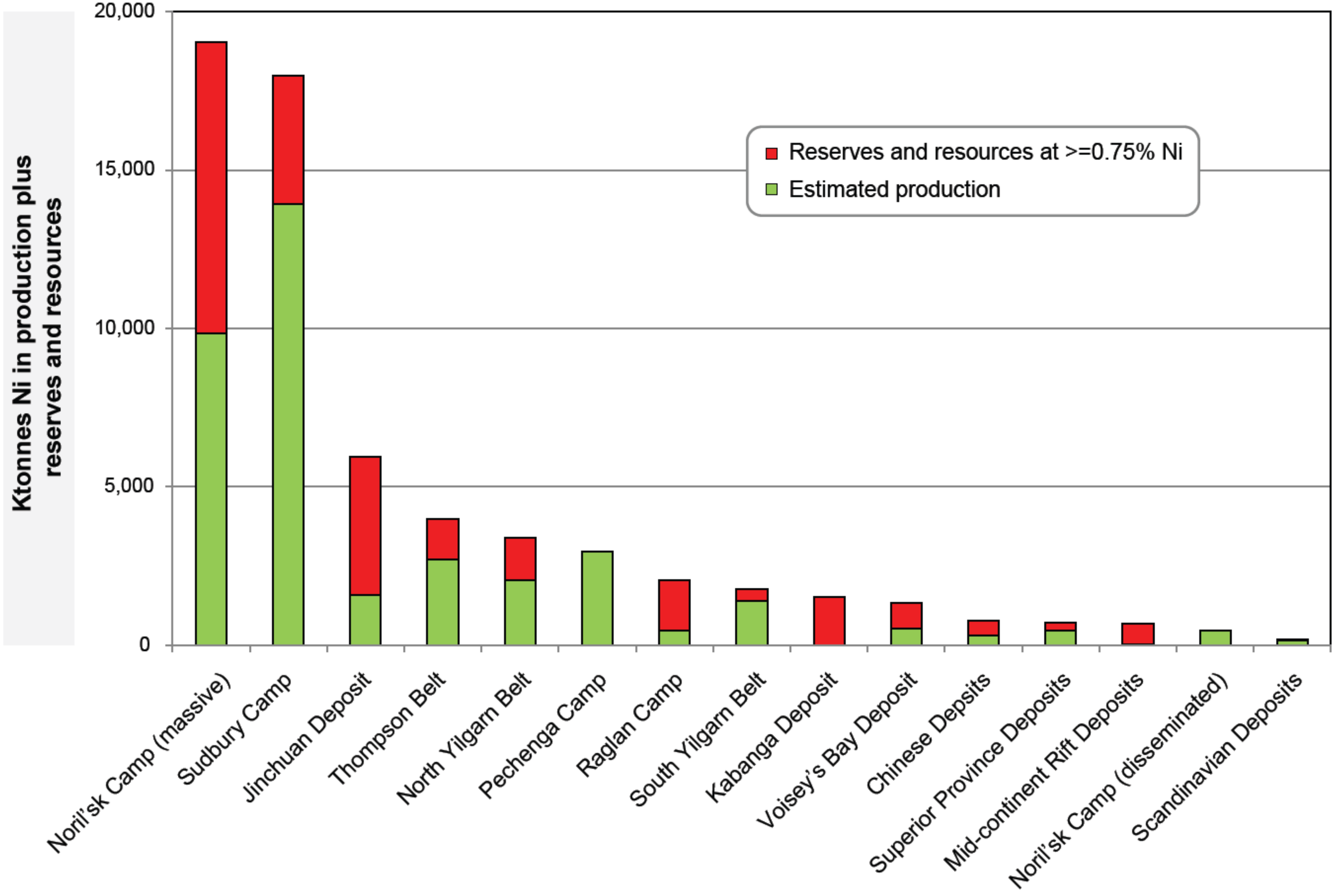
Contained nickel and produced nickel by camp (deposit)

Noril'sk is the largest Ni-Cu-PGE Deposit in the World

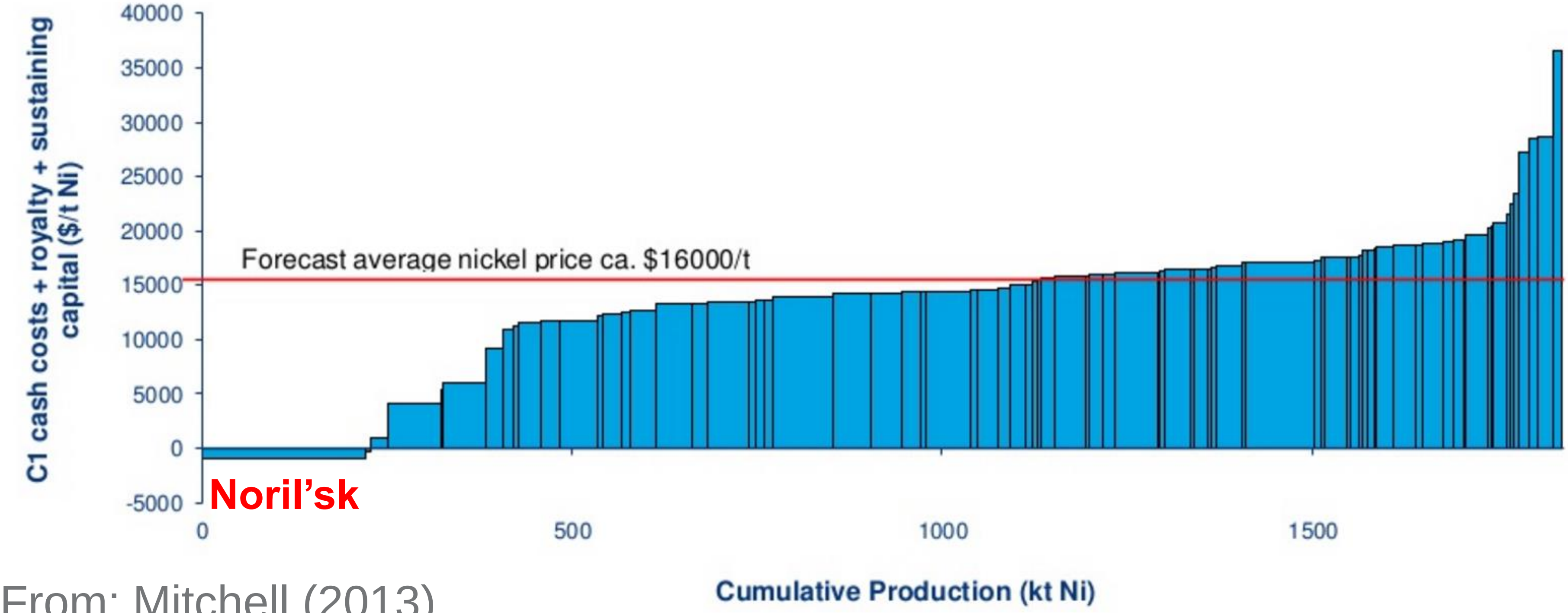


Lightfoot (2016)

Economics of Noril'sk Nickel

Negative cost of Ni production on global sulfide cost curve

Giant reserves and resources to support future production



From: Mitchell (2013)

Ore type	Deposit group	Category	Ore, Mmt	Ni wt%	Cu wt%	Pd g/t	Pt g/t	Au g/t	6E g/t	Ni kt
Ni-rich	Talnakh	PP+MII	257	2.96	3.59	6.76	1.36	0.22	8.61	7593
Cuprous	Talnakh	PP+MII	158	0.94	3.93	8.86	2.22	0.63	11.28	1477
Disseminated	Talnakh-Noril'sk	PP+MII	1961	0.49	0.99	2.99	0.91	0.19	4.08	9573

Noril'sk Nickel, 2015: Polar MRMR

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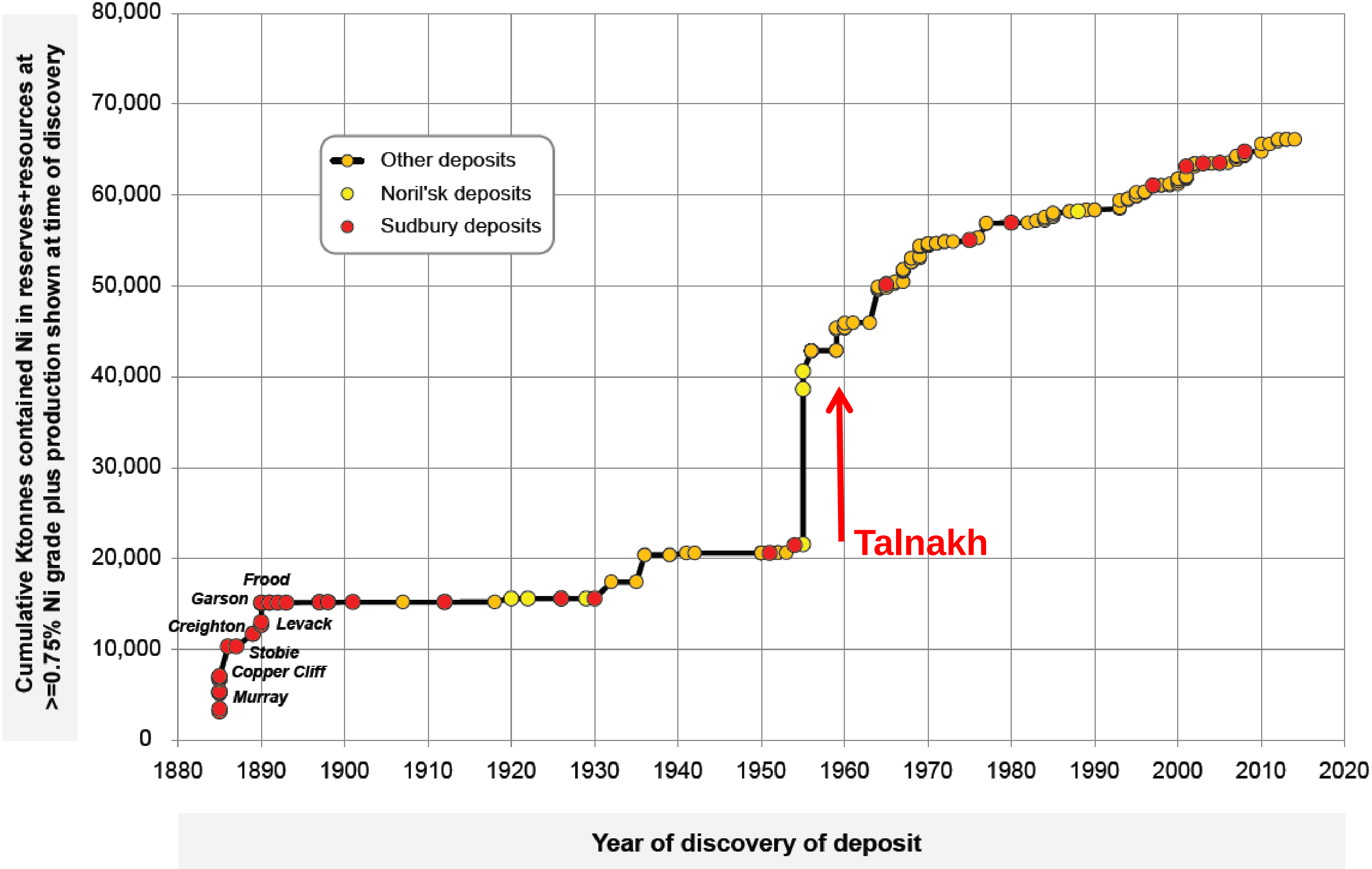
The Noril'sk Discoveries

Contained Ni at time of discovery (all deposits >0.75% Ni)



History of the Noril'sk Mining Camp

Major events (initial discovery):

- Bronze-age artifacts
- 1866: Staked for Cu and coal
- 1915: Re-staked
- 1920: Urvantsov identified Cu-Ni minerals (Sudbury analogue)
- 1923: First shaft (Noril'sk 1)
- 1935: Noril'sk Kombinat established

Gulag history:

- Norillag: Norilsk gulag 1935-1956
- Labor force constructed the Norilsk mining-metallurgic complex
- Peak of 72,500 prisoners in 1951
- Total number of inmates ~400,000 (includes 300,000 political prisoners).
- 1953: Noril'sk Uprising (Gorlag revolt)

Built on melting permafrost – entire infrastructure of city and mining camp

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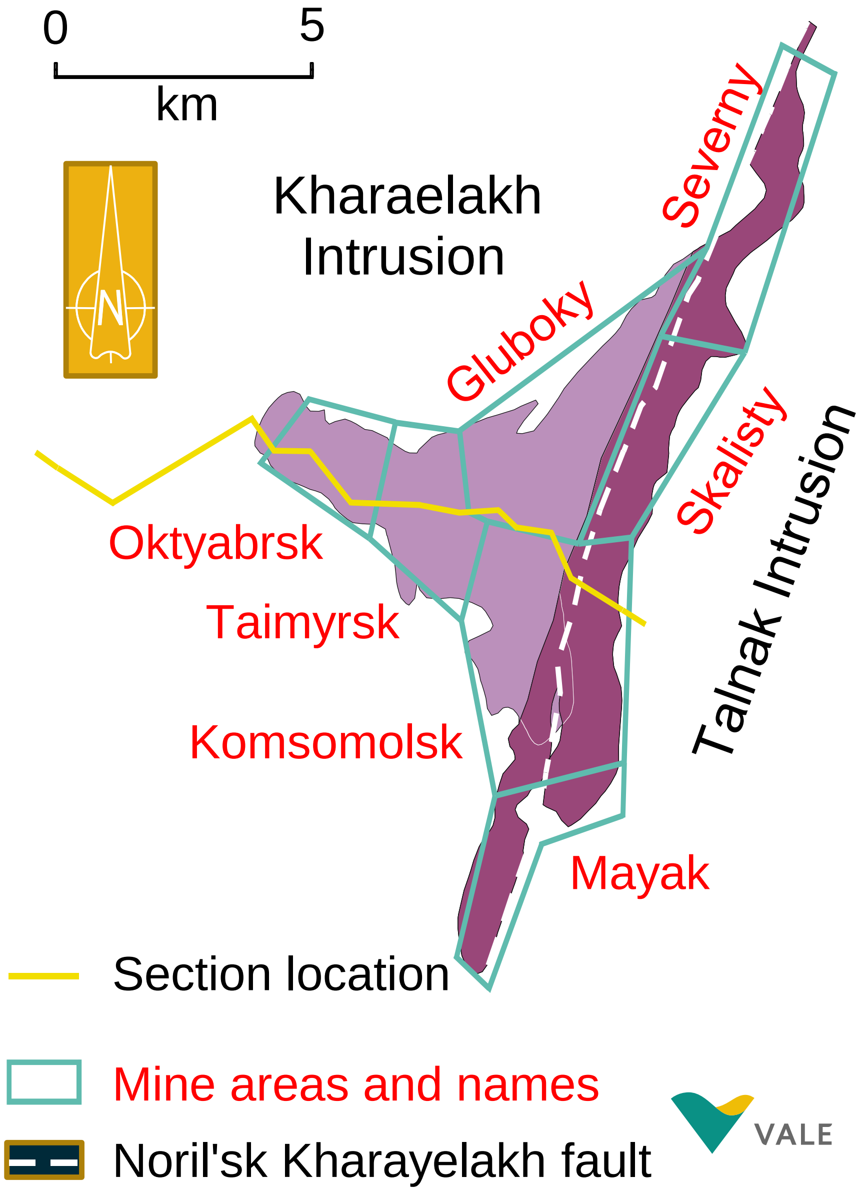
History of the Mining Camp

Major events:

- 1960:Talnakh mineralisation discovered in boulders and scree
- 1966: Mayak Mine commissioned
- 1971: Komsomolsk Mine commissioned
- 1974: Oktyabrysk Mine commissioned
- 1982: Taimyrsk Mine commissioned
- 2004: Skalisty Mine ramping-up
- 2013: Sverny-Gluboky mine plan and construction



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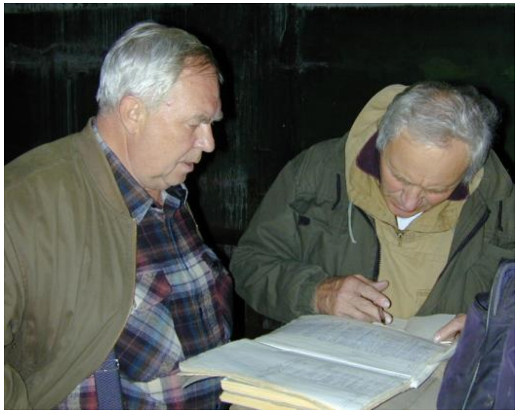
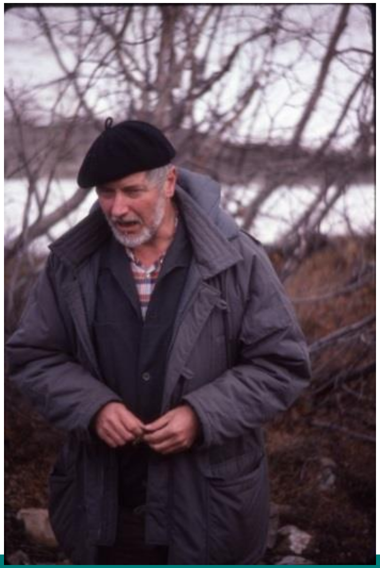
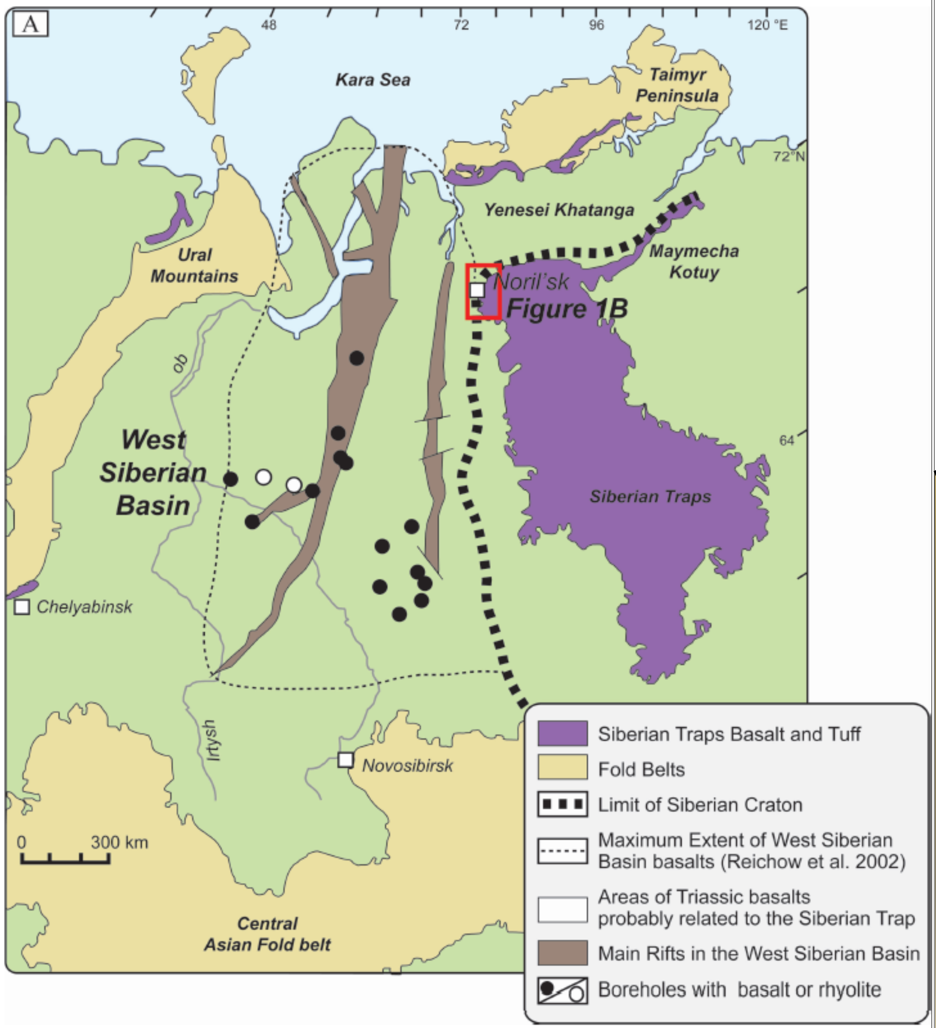
The Pathway to the Noril'sk Project

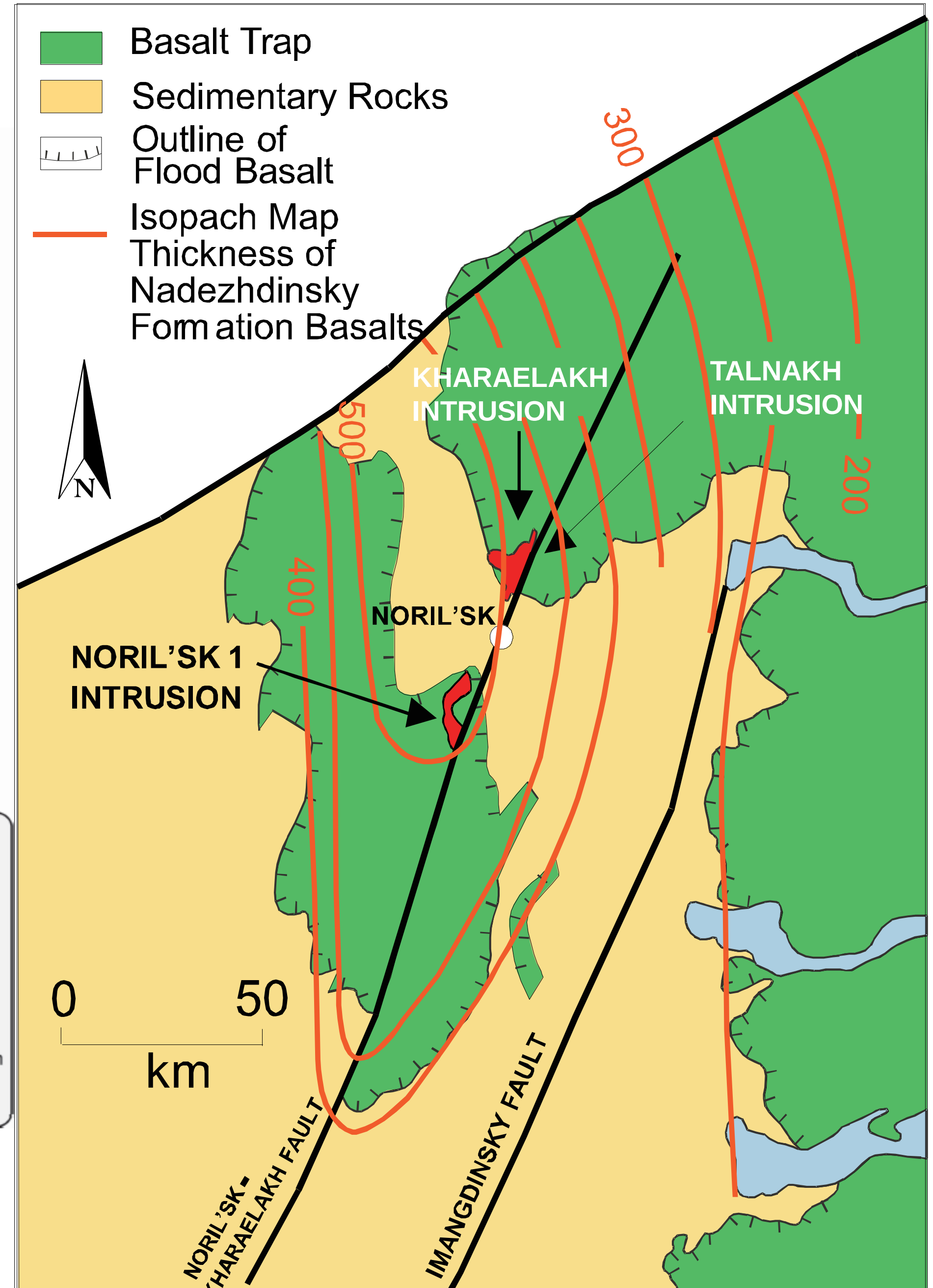
- 1985: USSR closed door (Chernenko, Andropov cronies)
- 1986: Chernobyl
  - Nick Gorbachev – PCL secured plan to work on basalt geochemistry/chemostratigraphy with IES USSR Ac Sci
  - 1987: first basalt samples arrived (SG-9)
  - Tony Naldrett joined project (ore deposits)
- 1988: USSR opened door (Gorbachev: Perestroika and Glasnost)
  - Valeri Fedorenko (TsNIGRI) joined project (geology)
  - 1988: Chris Hawkesworth joined project (radiogenic isotopes)
  - Copious samples arrived from basalt stratigraphy, intrusions, and ore deposits (and duplicated to USGS☺)
- 1989: Berlin Wall falls
- 1991: Soviet coup attempt: Yeltsin
- 1999: Door starts to close: Putin
  - 2000: Ed Ripley joins study (stable isotope study of basalts)
  - 2002: Visiting scientist IGEM Russia Ac Sci
    - Igor Zotov keeps foot in door
  - 2005: Reid Keays joins team (low level PGE study of basalts)
- ~2006: Door effectively closed
- 2016: Sample suite (basalts and intrusions) carefully retained for future work





Distribution of Siberian Trap Basalts



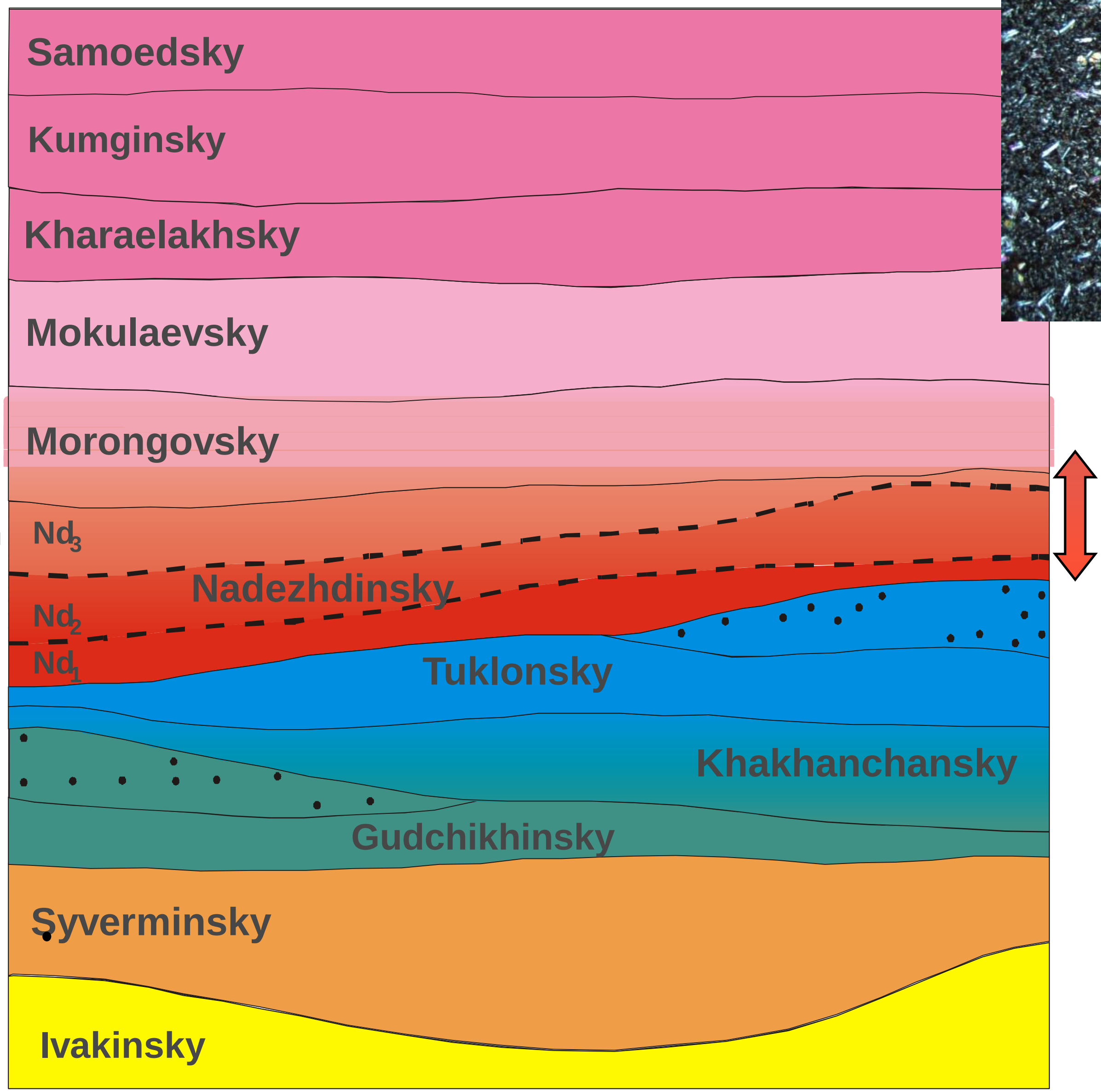


Lightfoot and Zotov (2014)

Naldrett et al (1995);

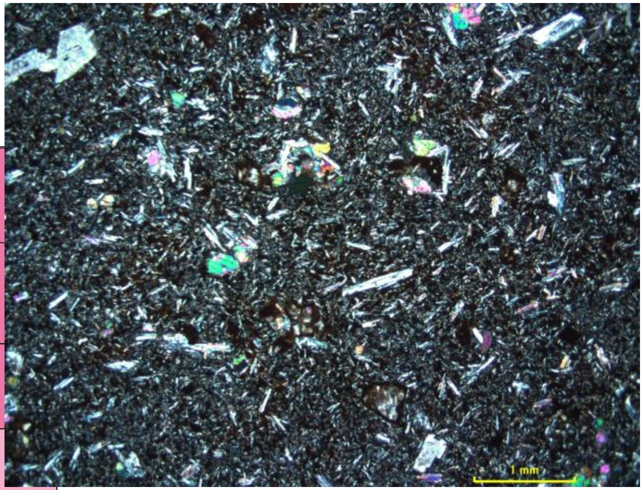
http://www.largeigneousprovinces.org/LOM.html

Basalt Stratigraphy of the Noril’sk Region



~ 3500 m

Lightfoot and Hawkesworth, 2001



Crustally-contaminated and Ni-Cu-PGE-depleted basalts

- Tholeiitic basalts
- Picritic basalt
- Alkalic and sub-alkalic basalts

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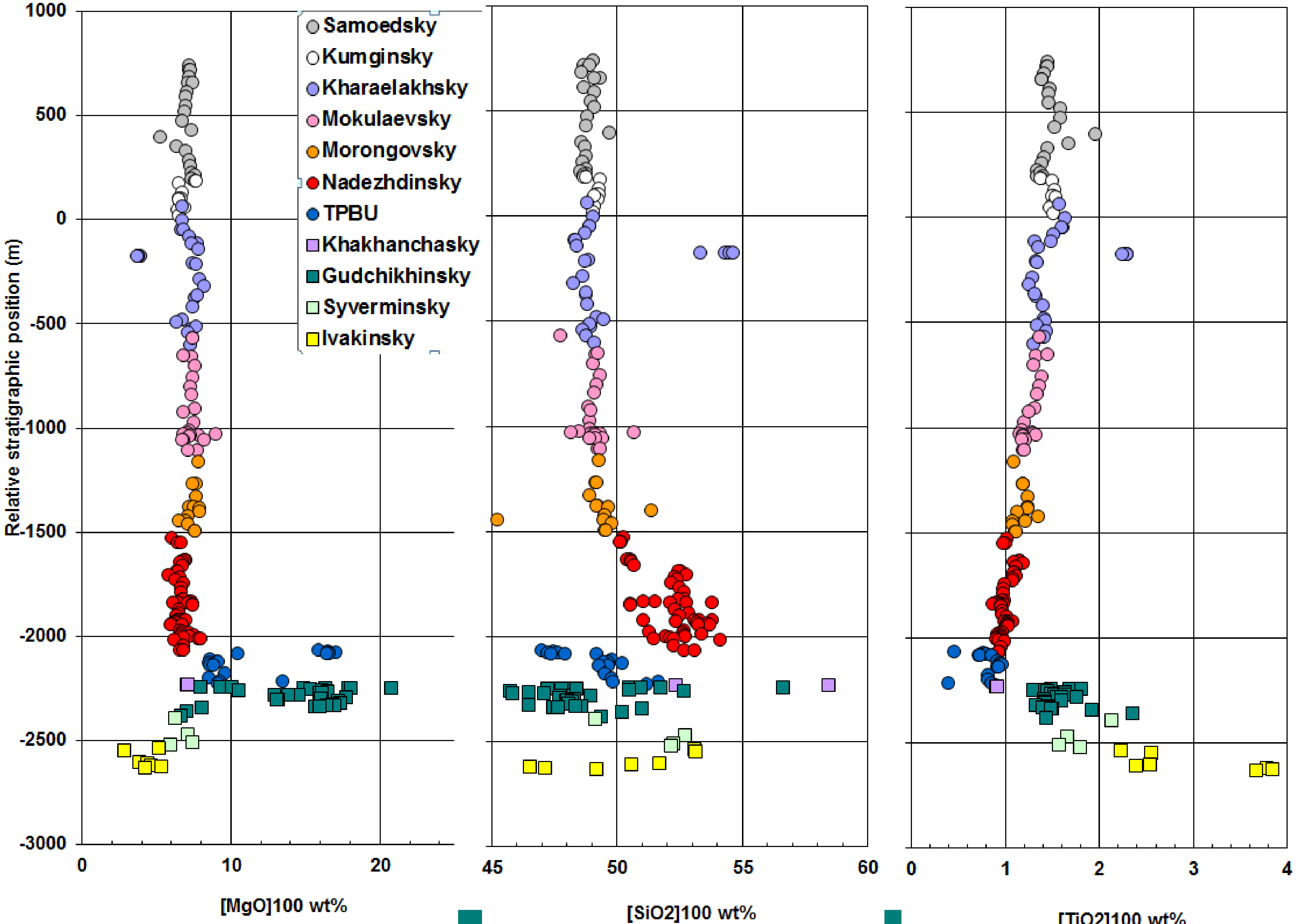
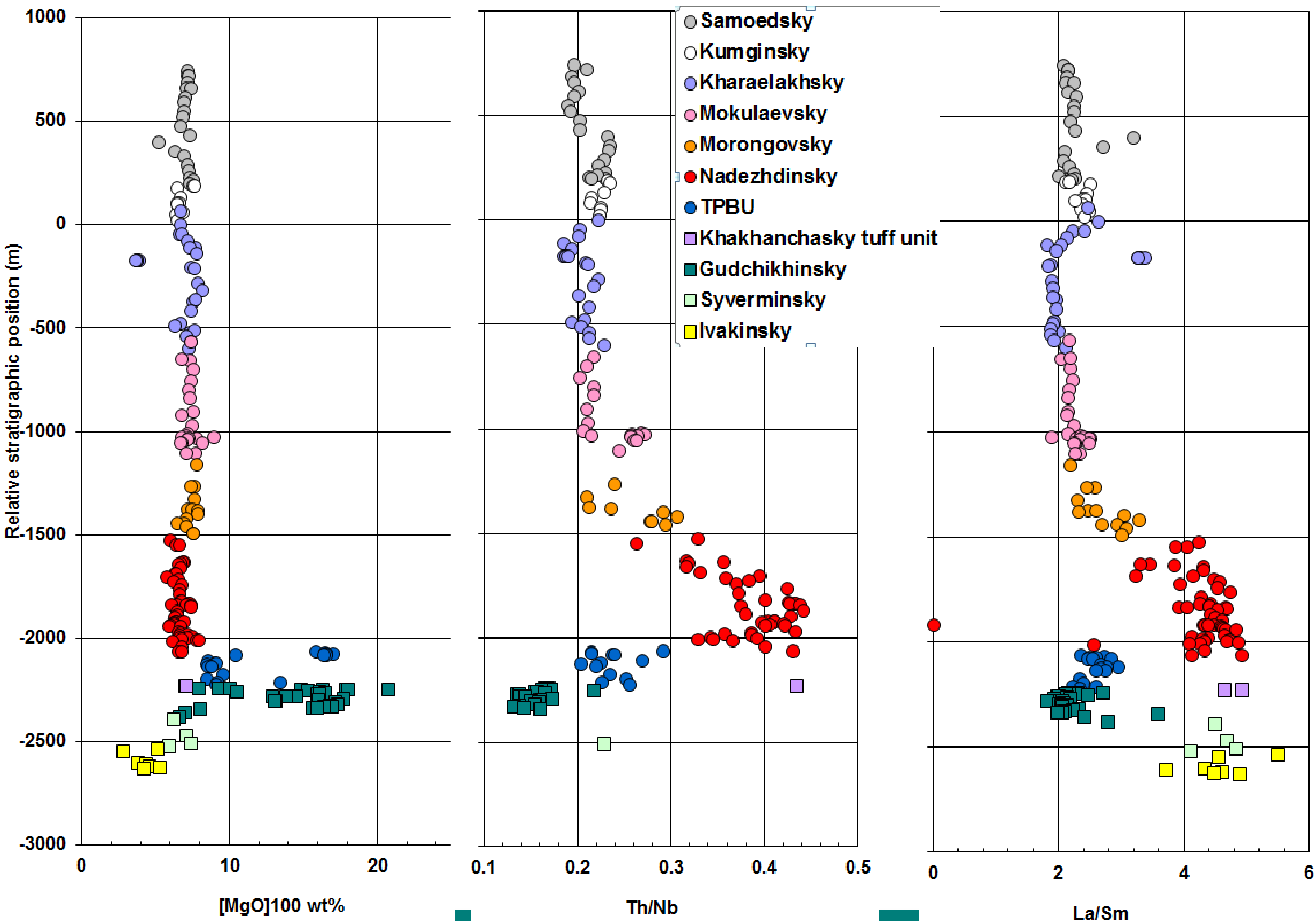
Basalt escarpment east of Talnakh: Iv-Sv-Gd-Nd Formation basalts

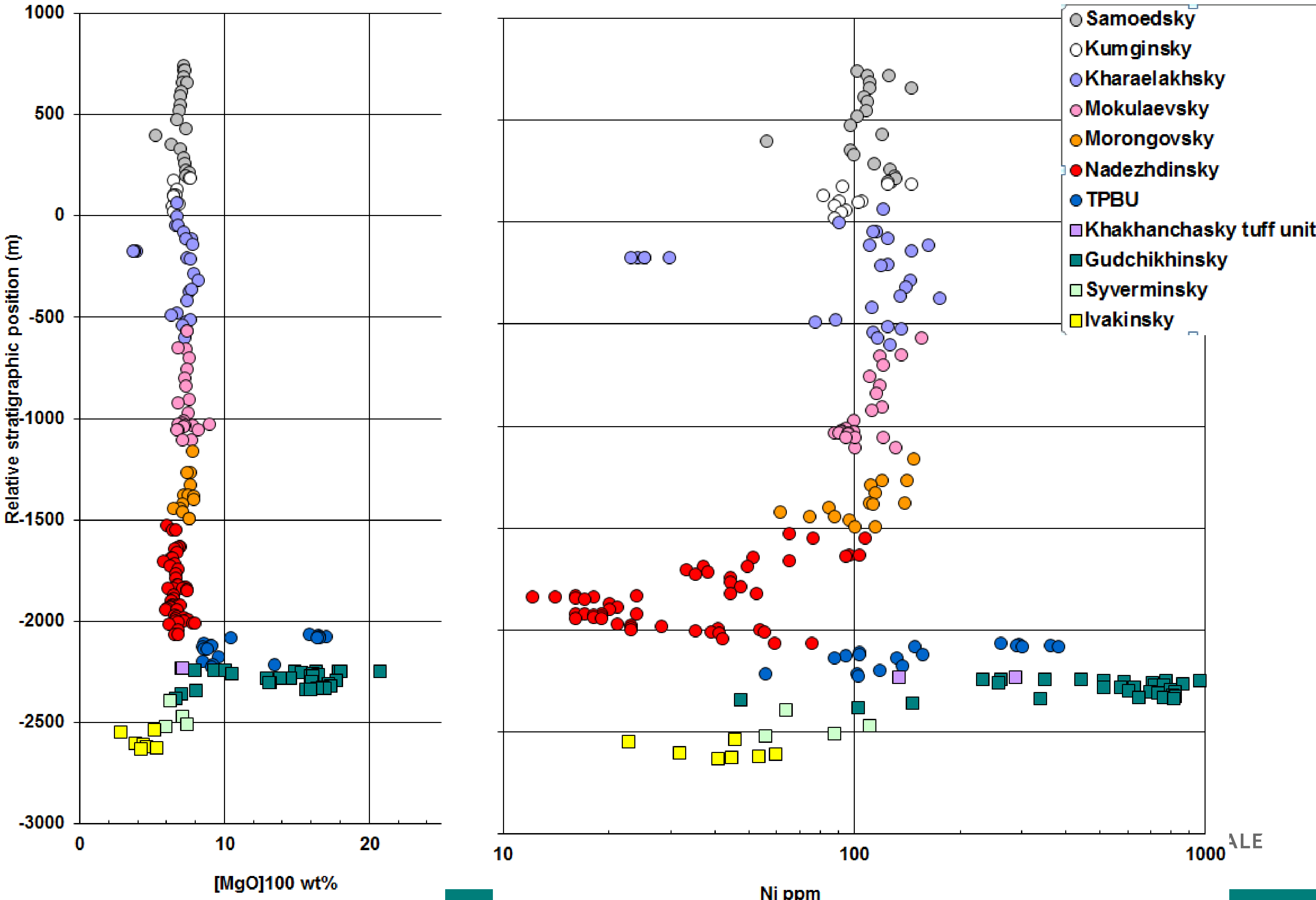
Composite Chemostratigraphy – Noril'sk



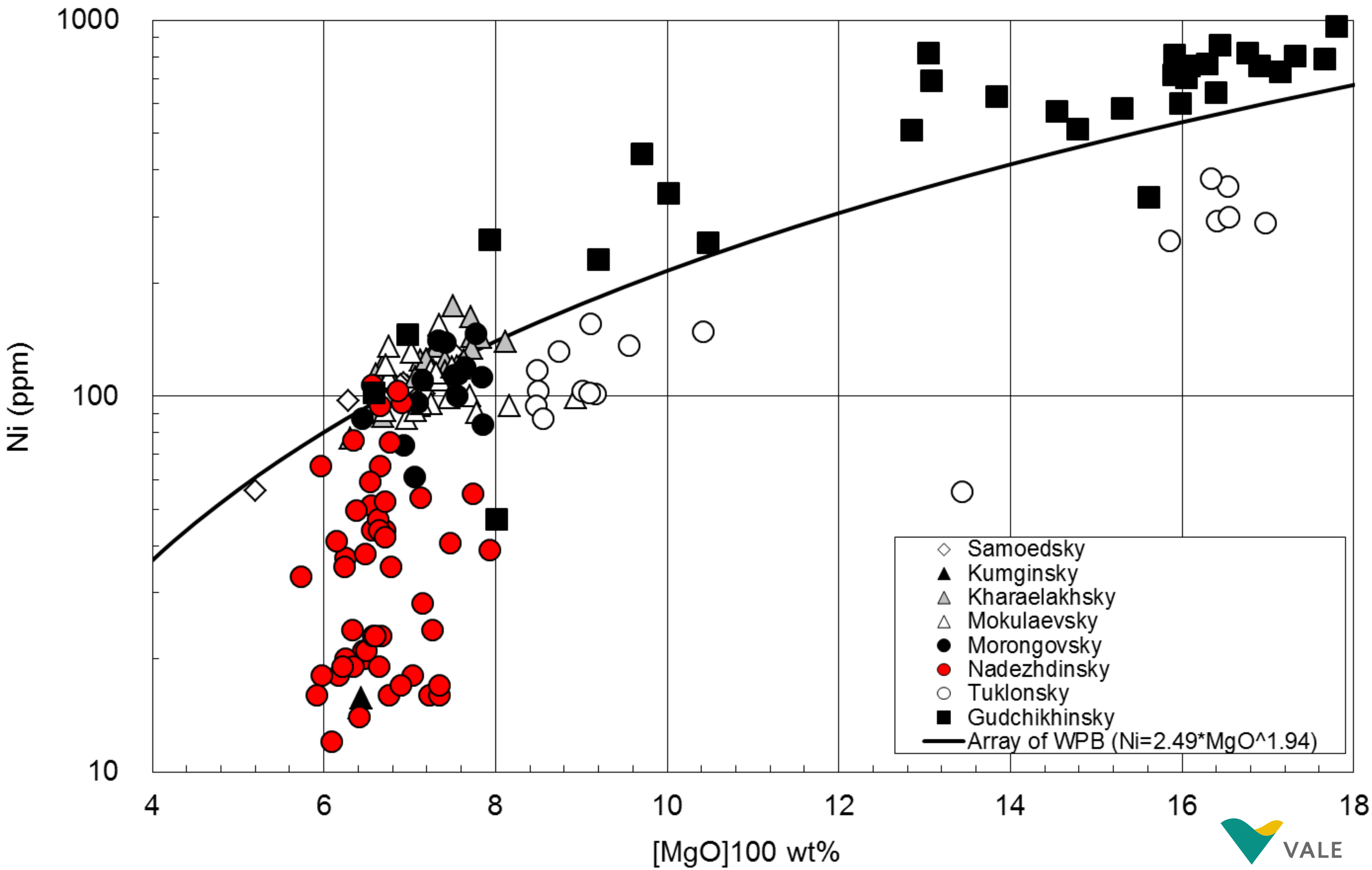
Composite Chemostratigraphy – Noril'sk Basalts



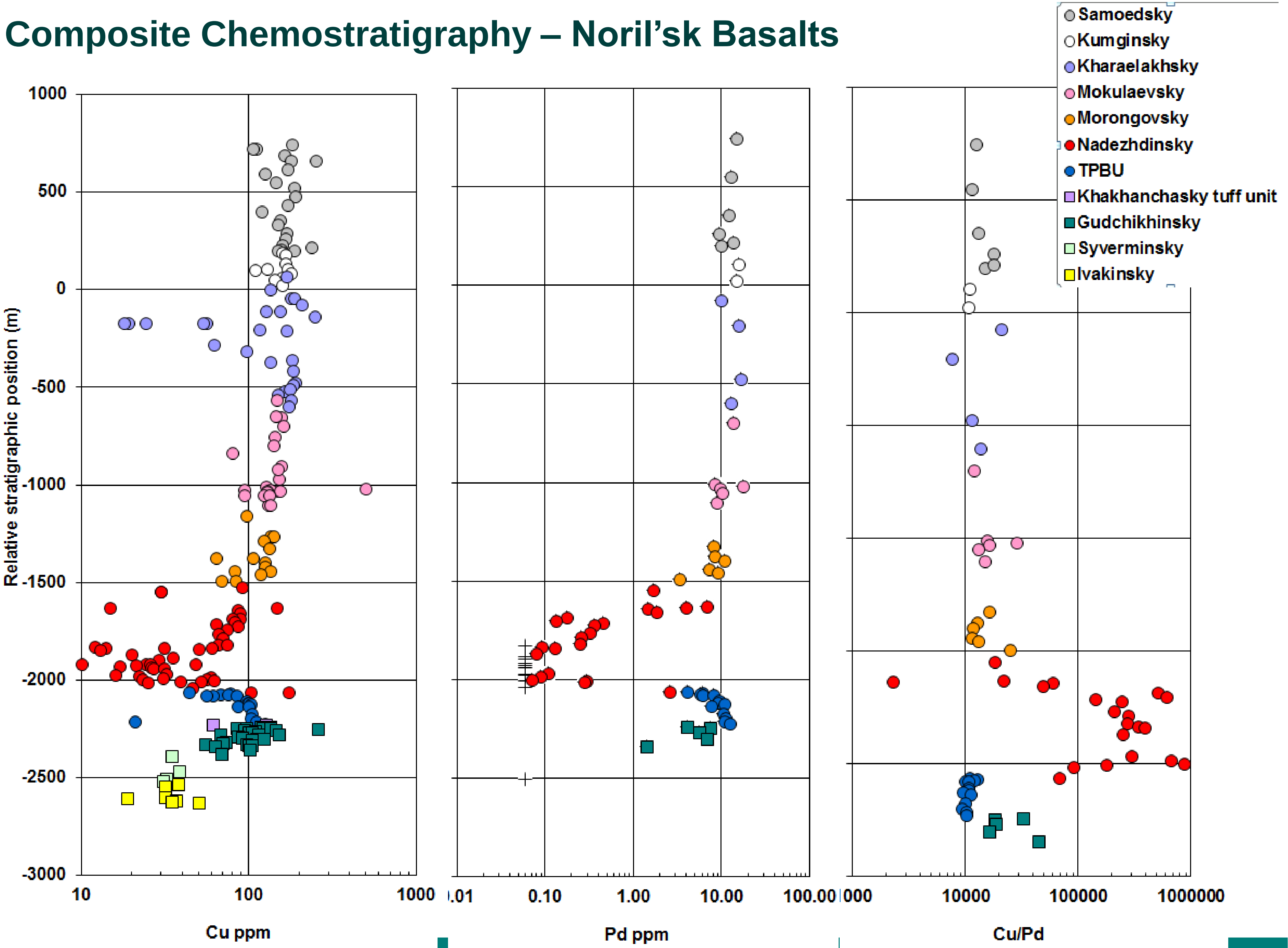
Composite Chemostratigraphy – Noril'sk Basalts



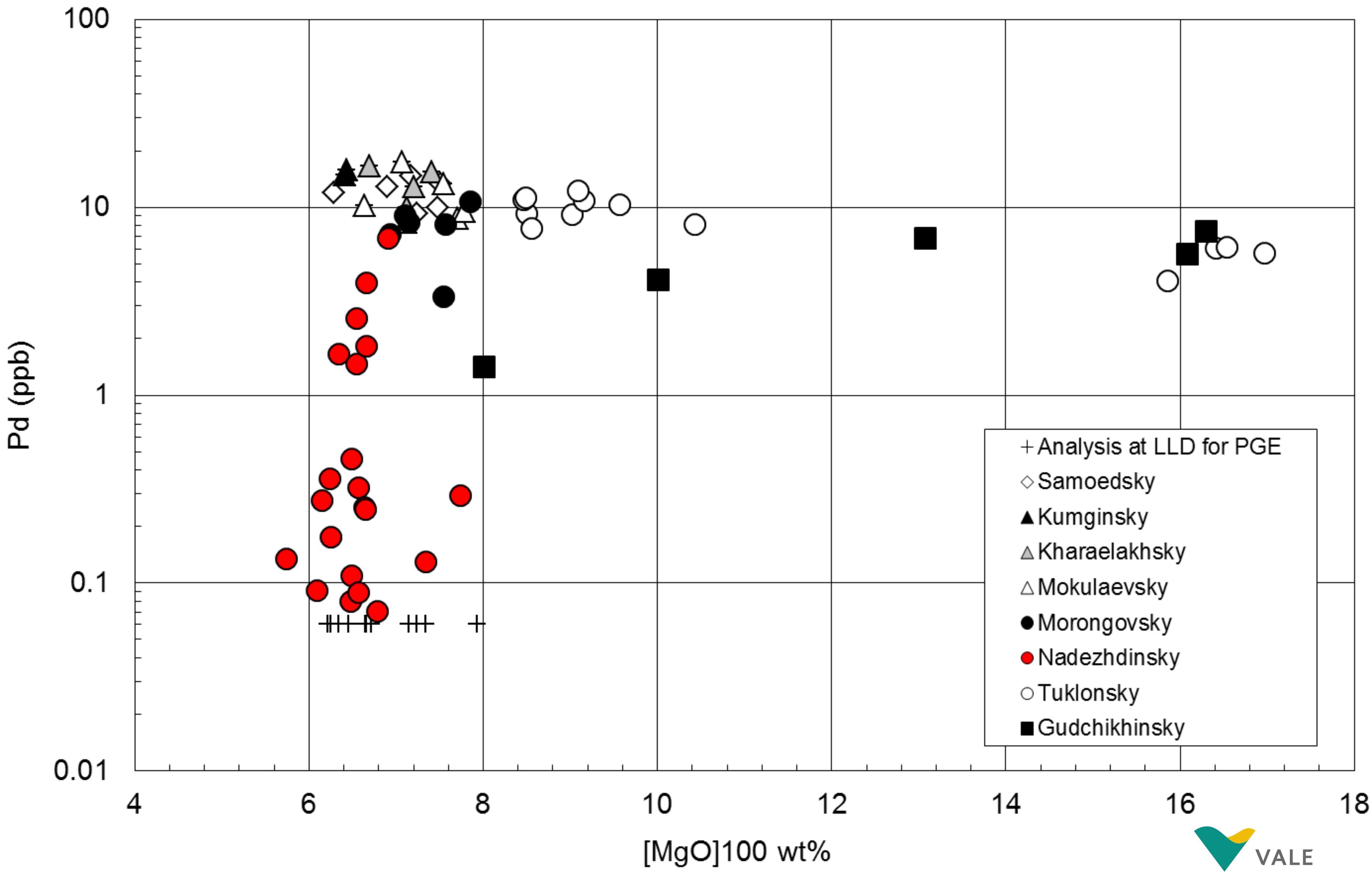
Siberian Trap basalts: MgO versus Ni



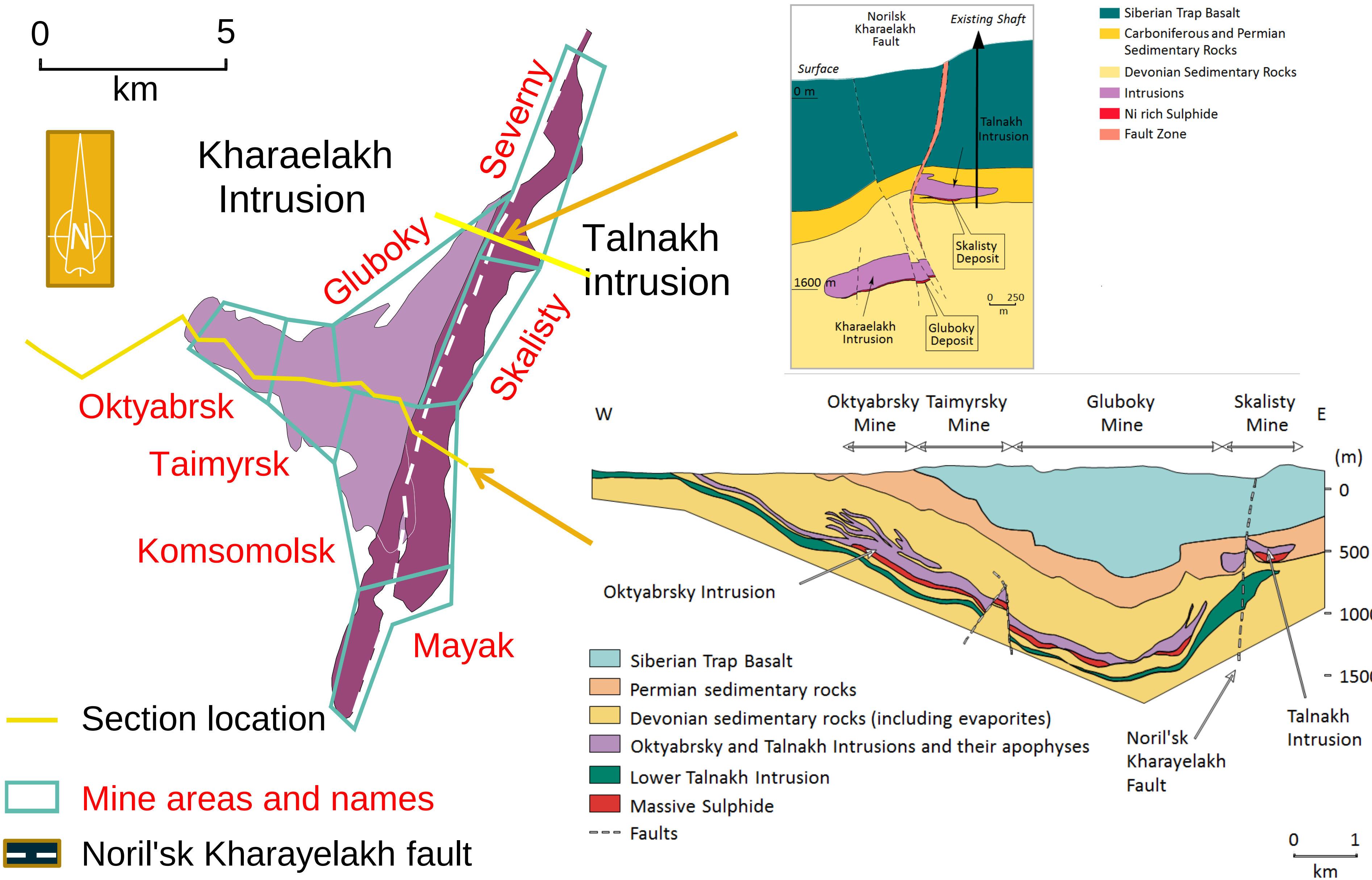
Composite Chemostratigraphy – Noril'sk Basalts



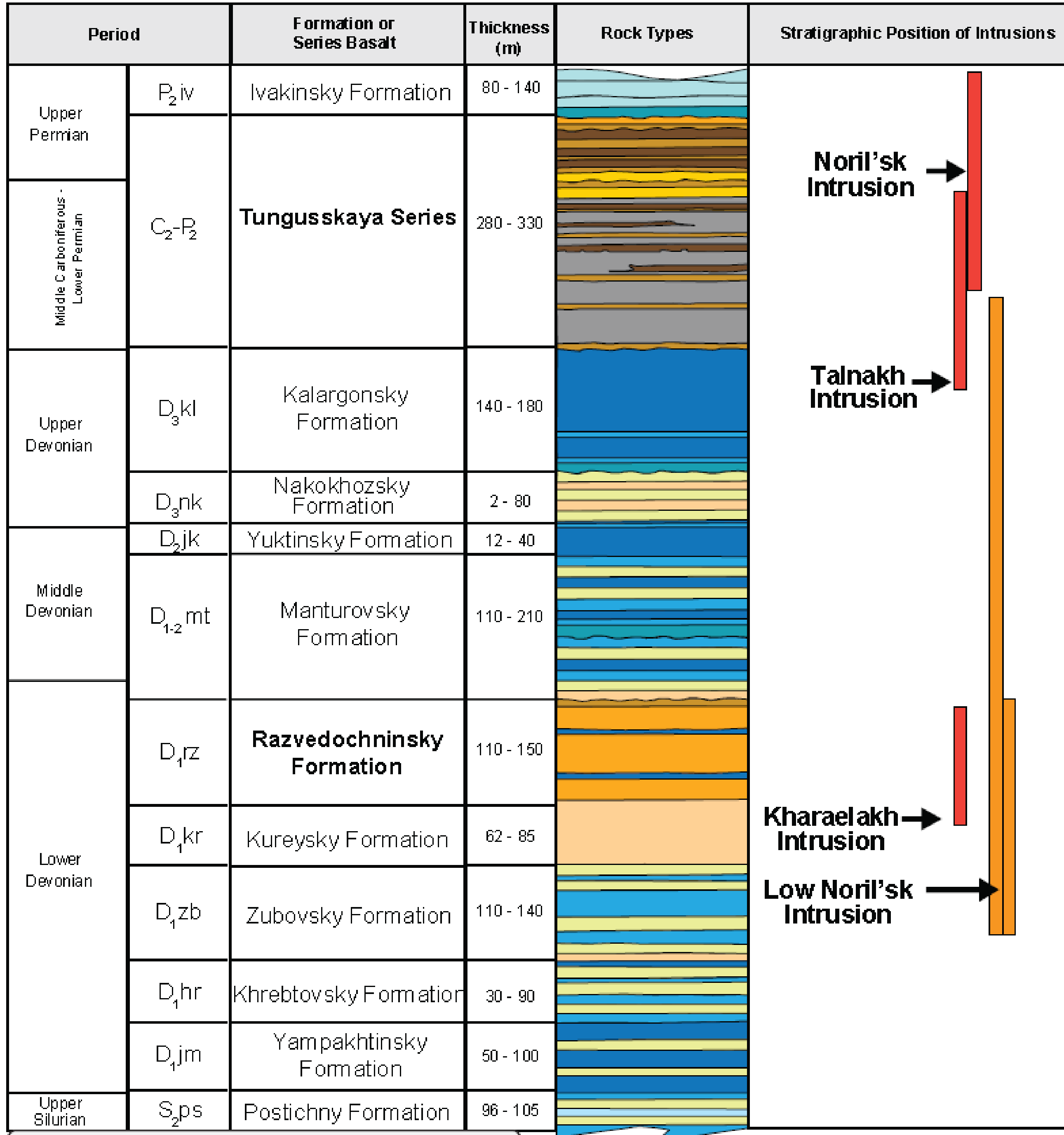
Siberian Trap basalts: MgO versus Pd

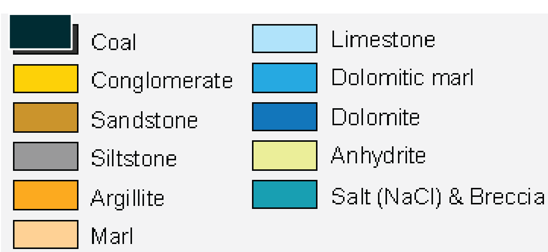


Distribution of mines on the Talnakh-Kharaelakh Intrusions

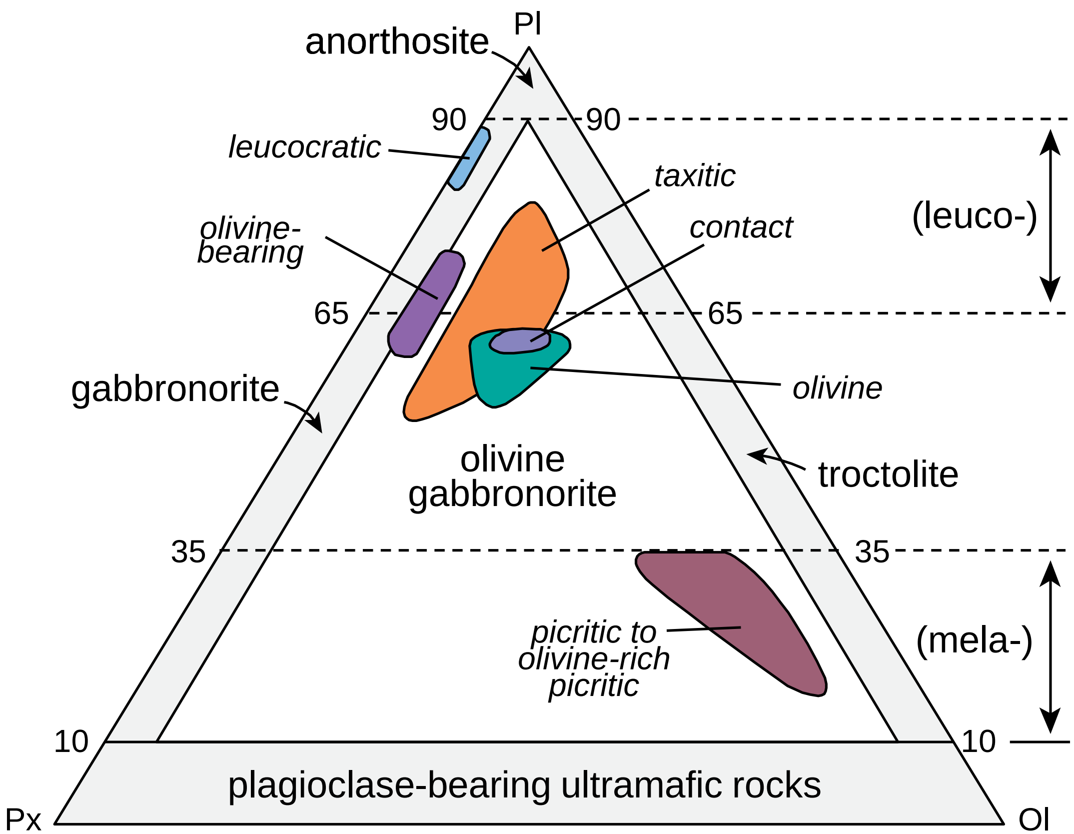


Stratigraphic column showing the position of differentiated intrusions in Devonian and Lower Permian sedimentary rocks





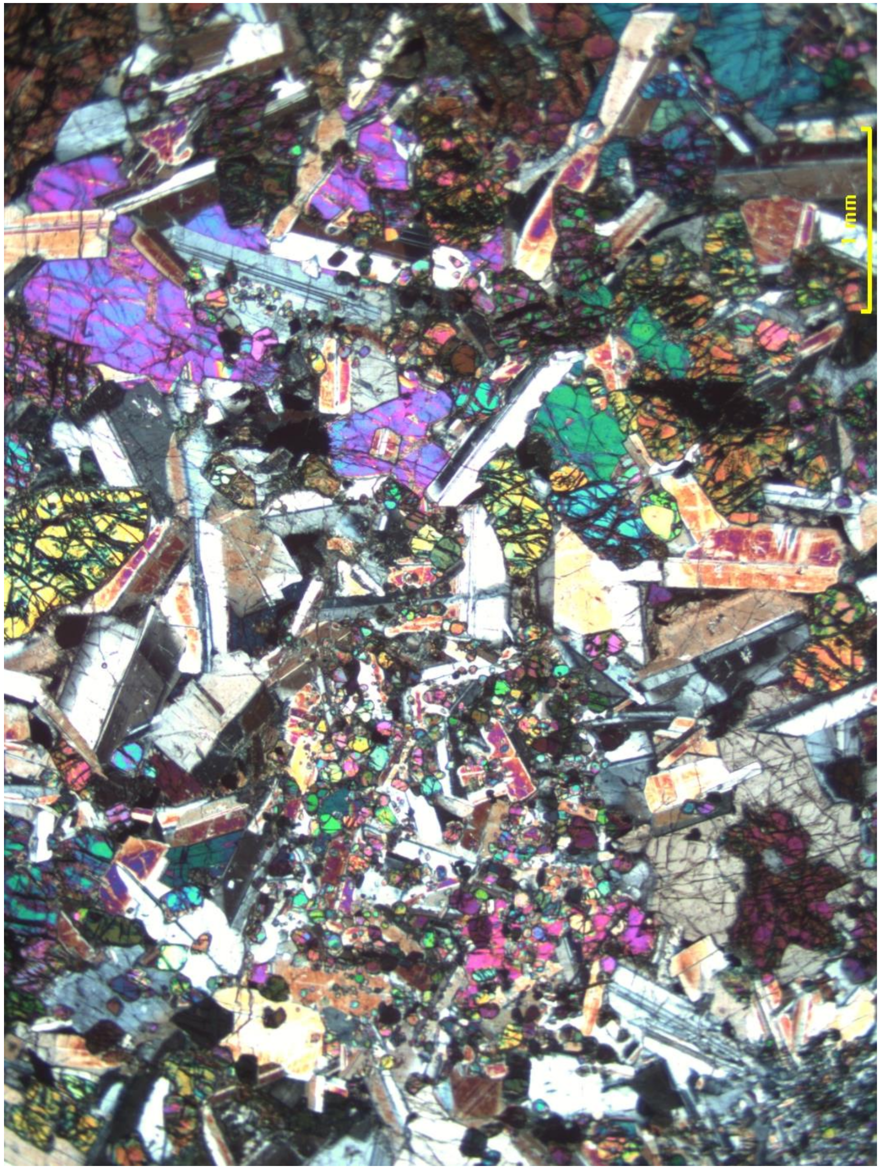
Petrology of the Talnakh and Kharaelakh Intrusions



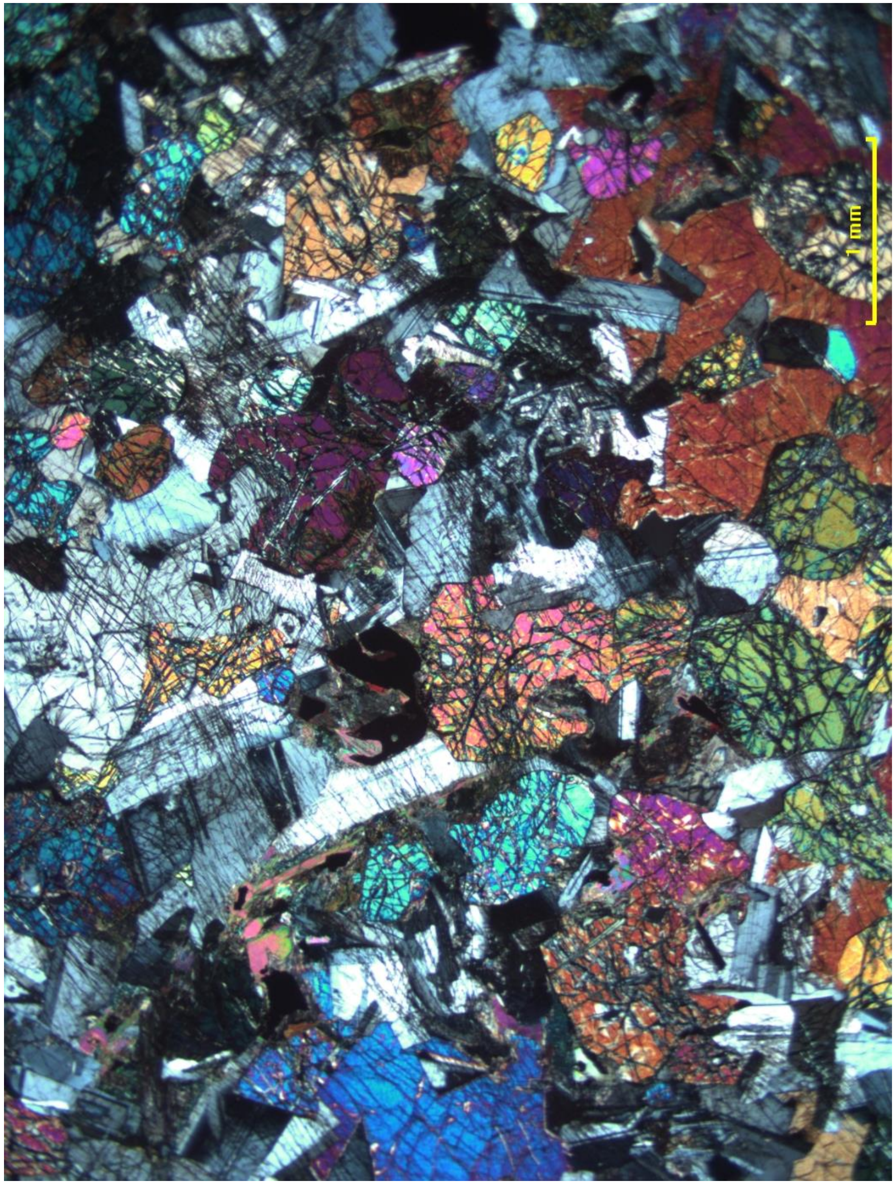
	Rock unit	Modal % olivine	MgO wt %	Important Minerals
	Leucocratic gabbro	0-3	4-8	Pl_1
	Quartz diorite *(Russian: quartz gabbrodiorite)*	0	1.2-1.7	Pl_2 + Aug + Qtz
	Magnetite gabbro	0-4	4.4-7	Pl_2 + Aug + Mt
	Prismatic gabbro *(Russian: gabbro-diorite)*	0-5	6-7	Pl_2 + Aug
GABBRODOLERITE	Olivine-bearing	3-7	6-8	Pl_2 + Aug + Ol_2
GABBRODOLERITE	Olivine	10-27	9-12	Pl_2 + Aug + Ol_2 + sparse Pl_1
GABBRODOLERITE	Picritic	40-80	18-29	Ol_1 + Pl_2 + Aug + Sulphide + Pl_1 glom + sparse Pl_1
GABBRODOLERITE	Taxitic	7-18	9-16	Pl_2 + Ol_2 + Aug + Sulphide + Pl_1 glom
GABBRODOLERITE	Contact	10-15	7-8	Pl_2 + Aug + Ol_2

Talnakh: Komsomolsk Mine
Lower Taxitic Gabbrodolerite

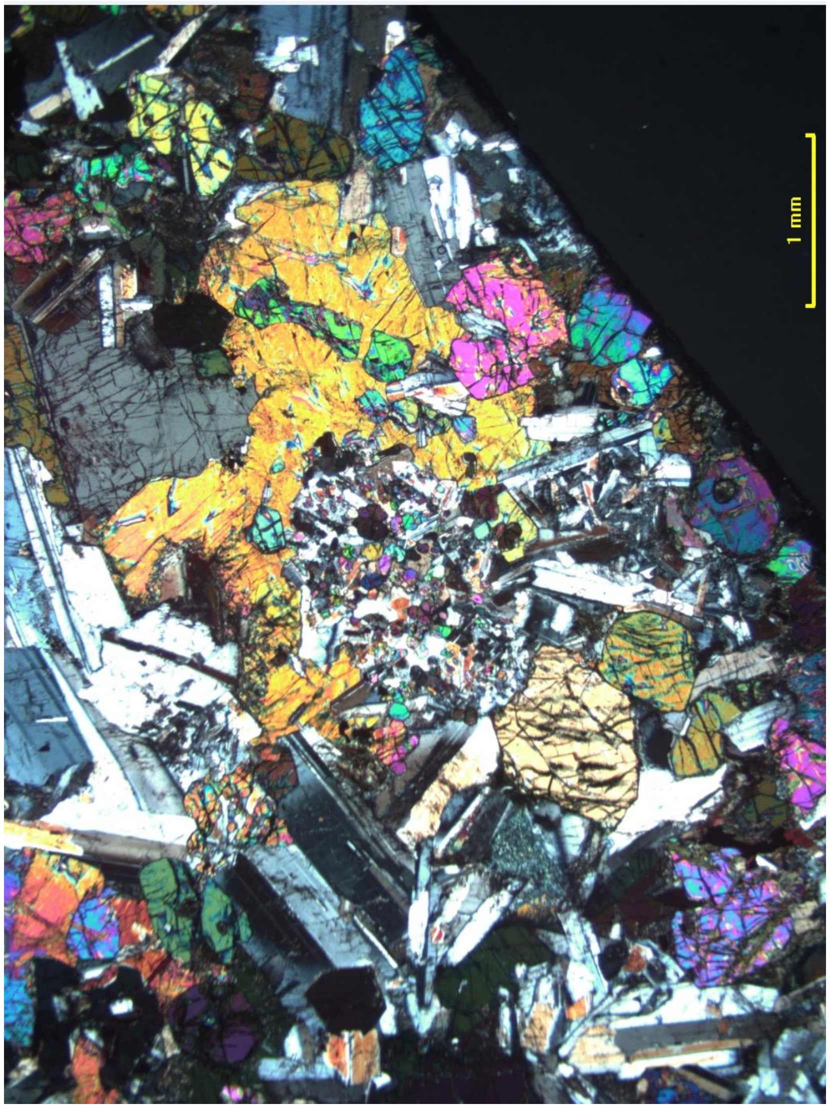
RX187911 (C03-0838) Taxitic gabbrodolerite, Noril'sk II Intrusion



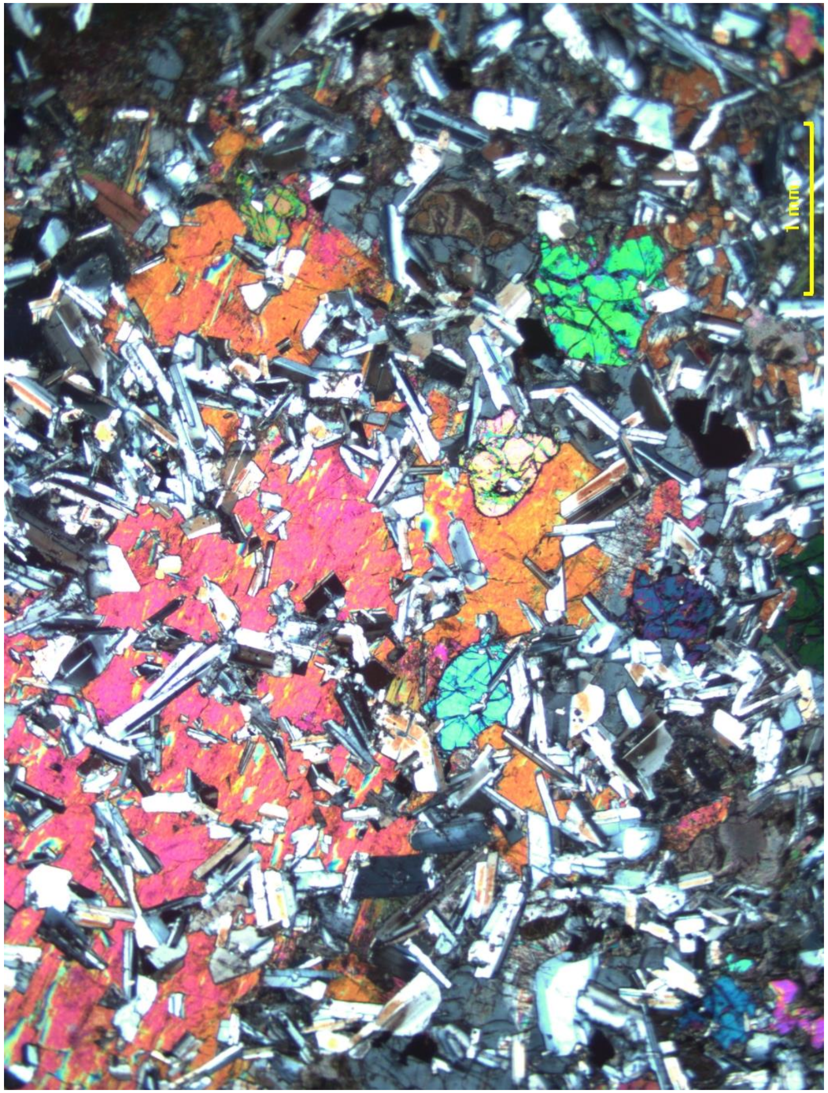
Picritic gabbrodolerite (C02-0590)



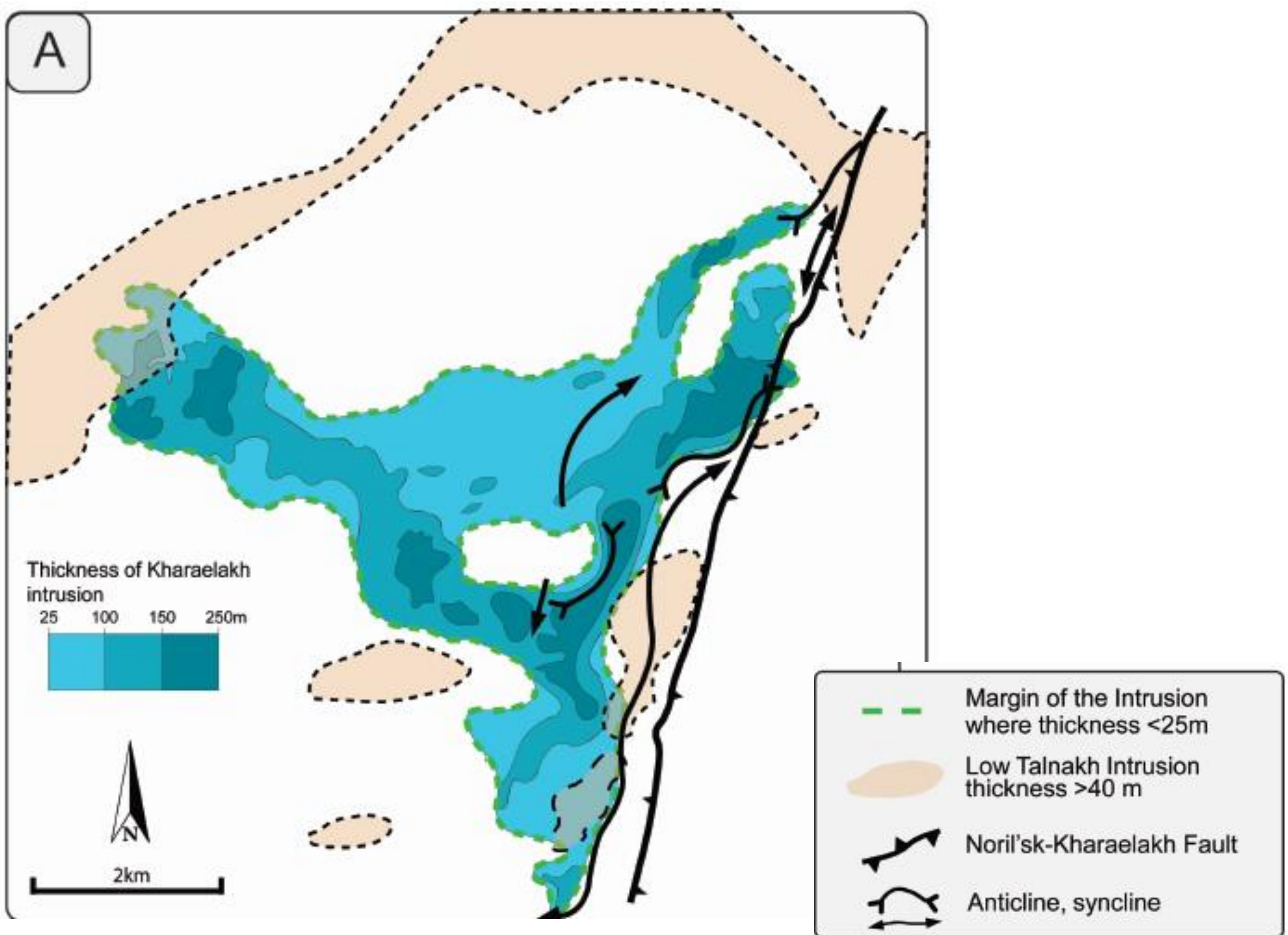
Olivine melagabbro (C02-0584)



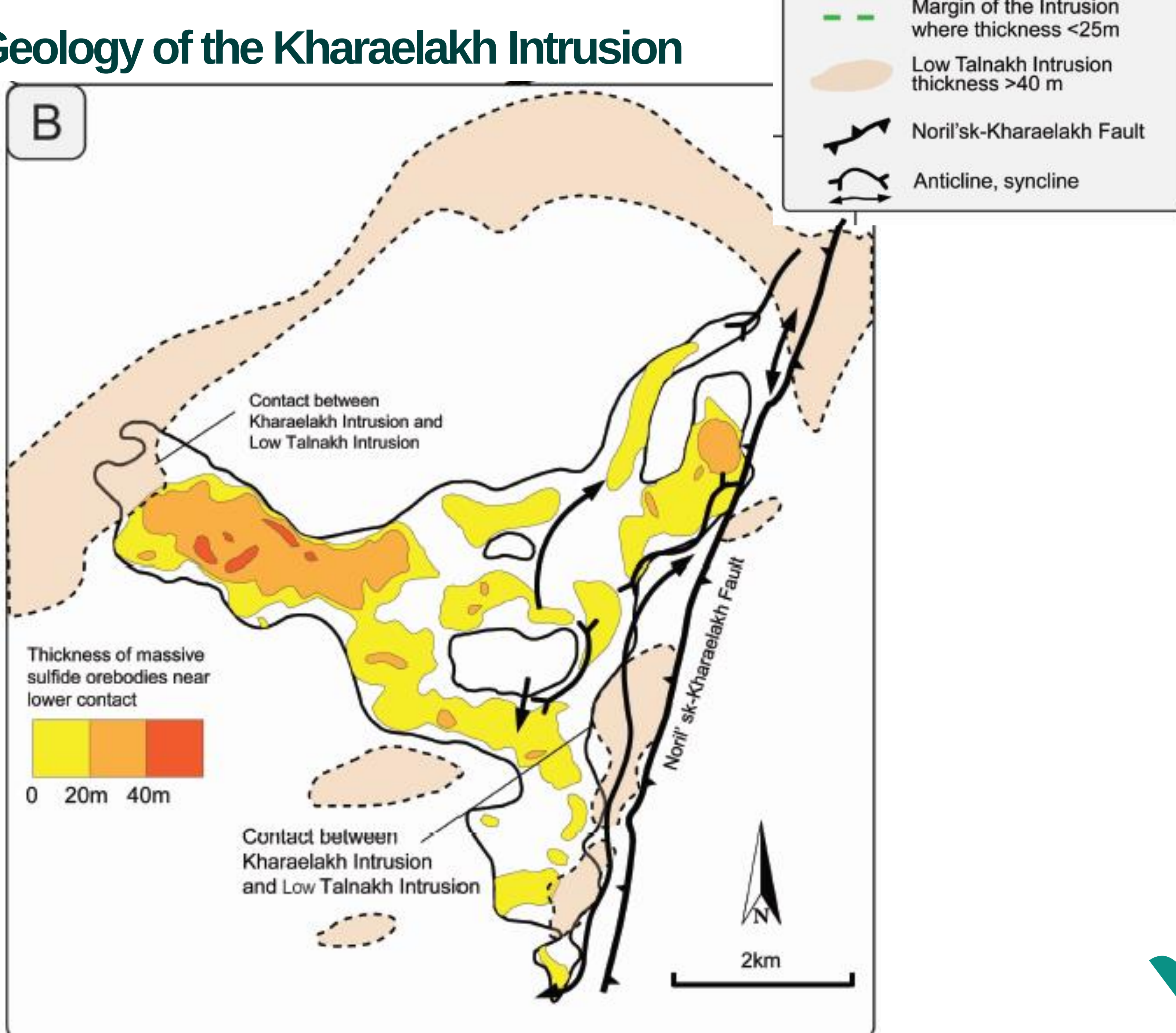
Olivine gabbrodolerite (C02-0583)



Geology of the Kharaelakh Intrusion



Geology of the Kharaelakh Intrusion



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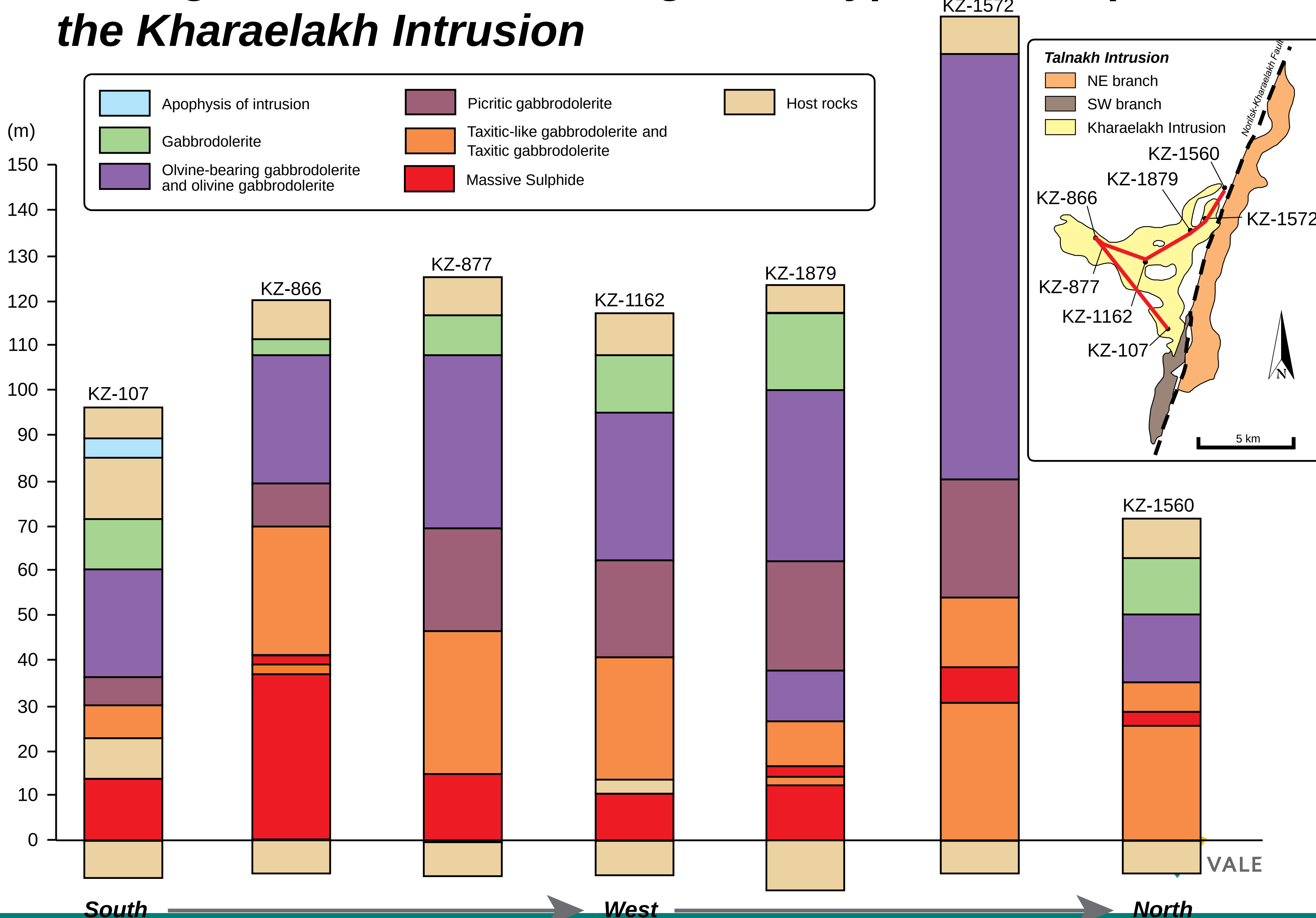
Geological Sections Showing Rock Types Developed in the Kharaelakh Intrusion



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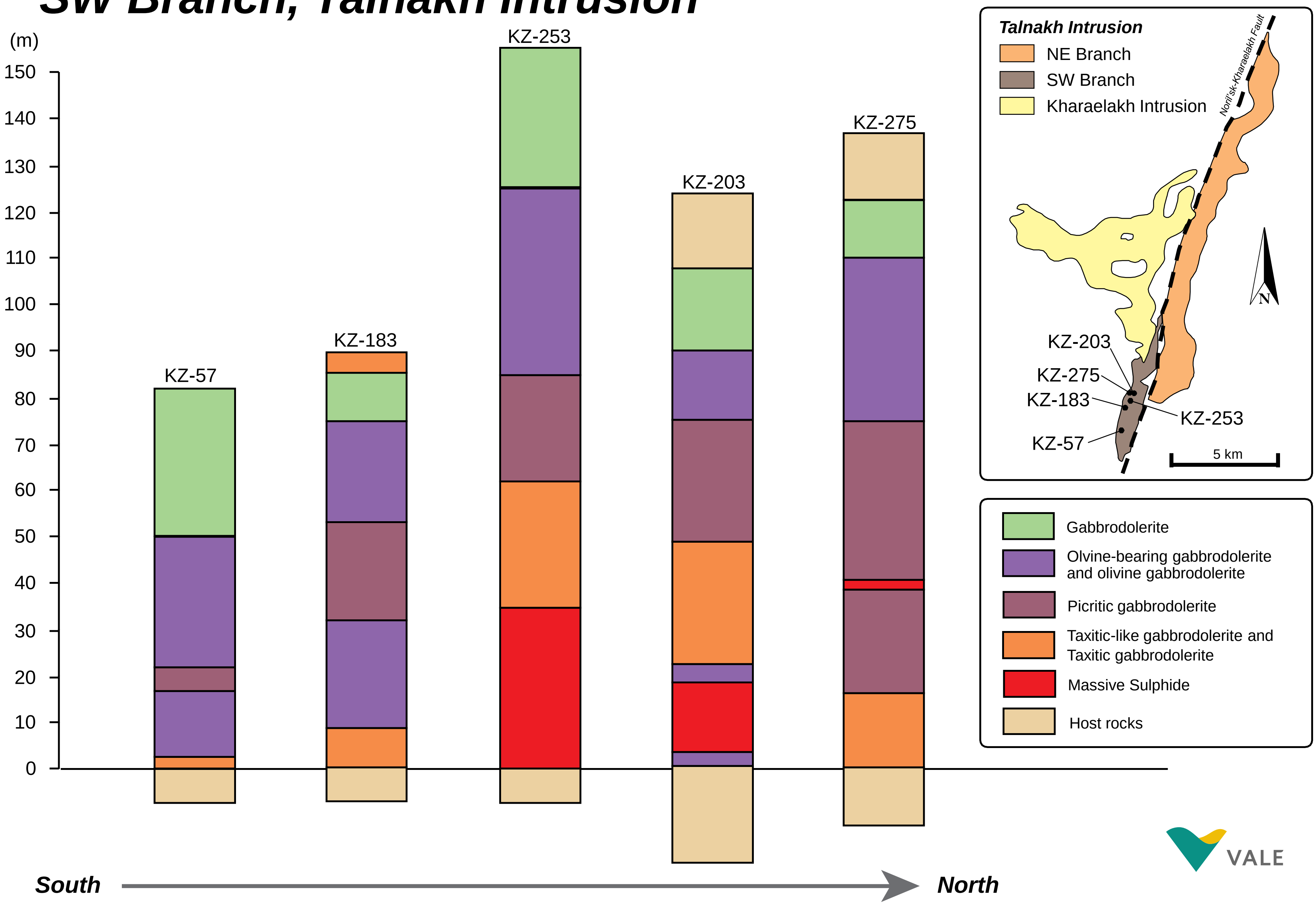
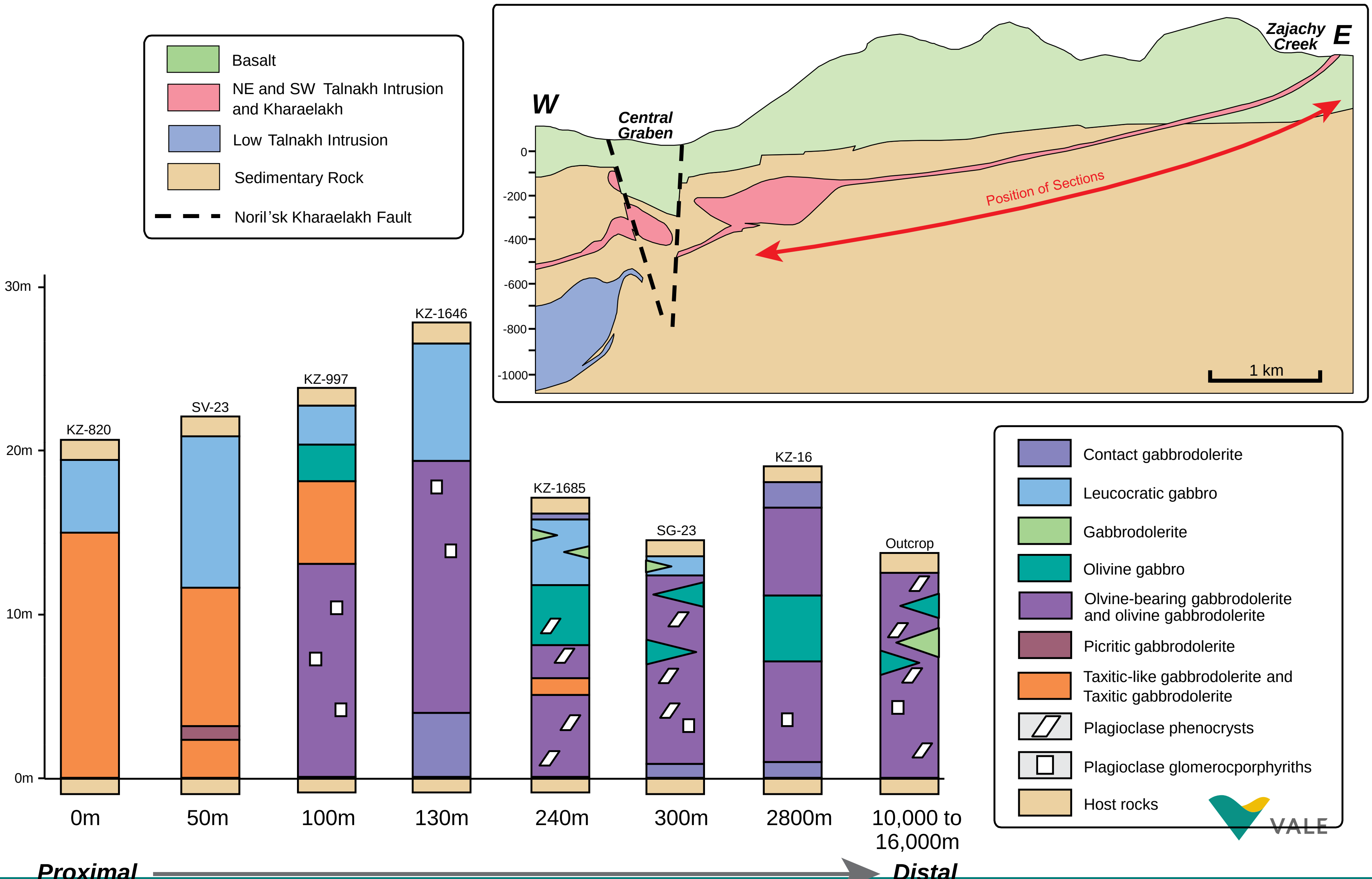
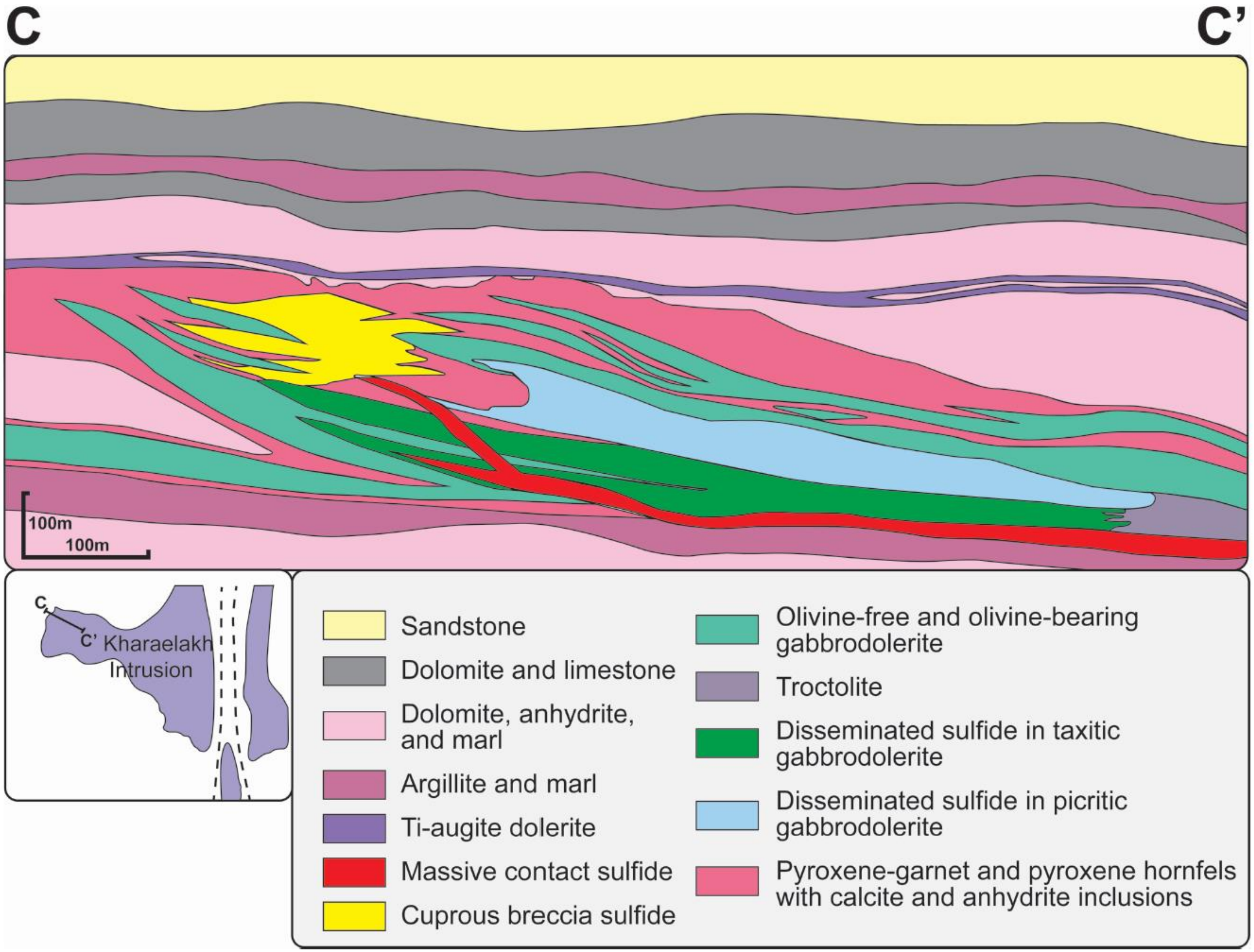
Geological Sections Showing Rock Types Developed in SW Branch, Talnakh Intrusion



Geological Sections Showing Rock Types Developed in Flanking Apophysis of the NE Talnakh Intrusion

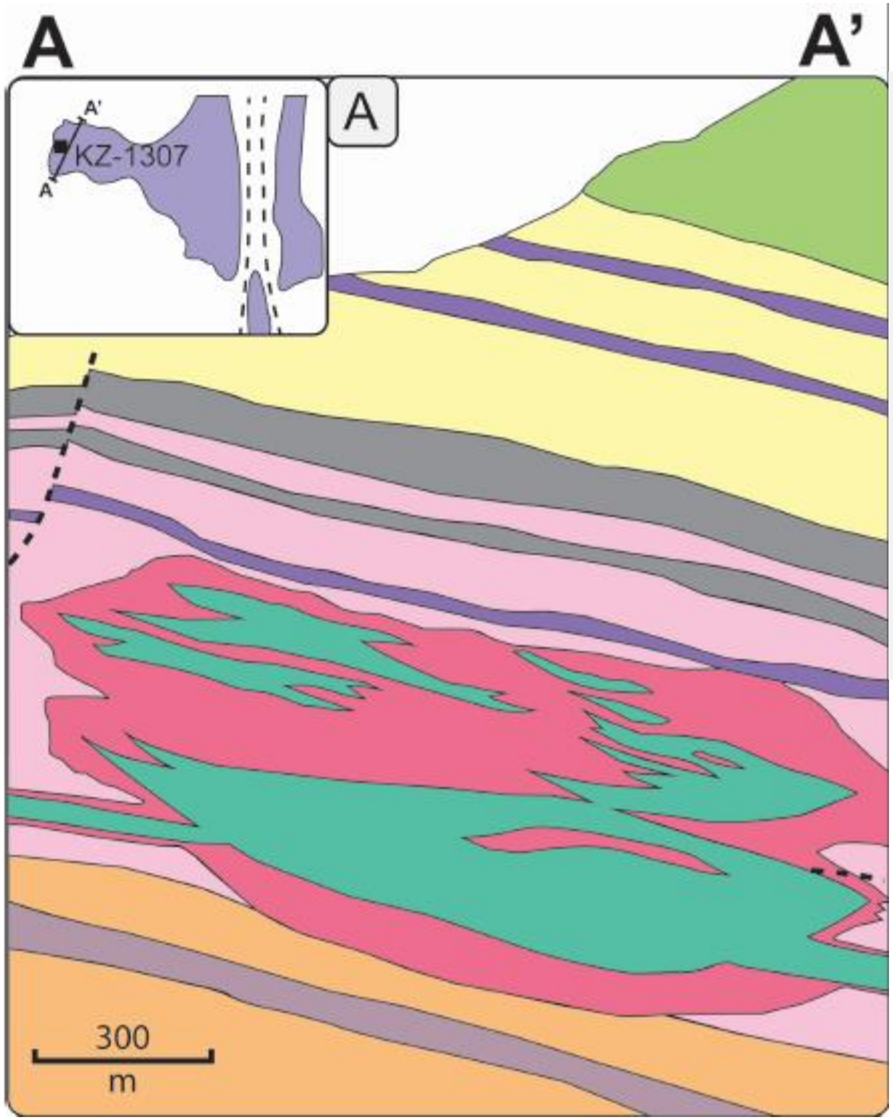


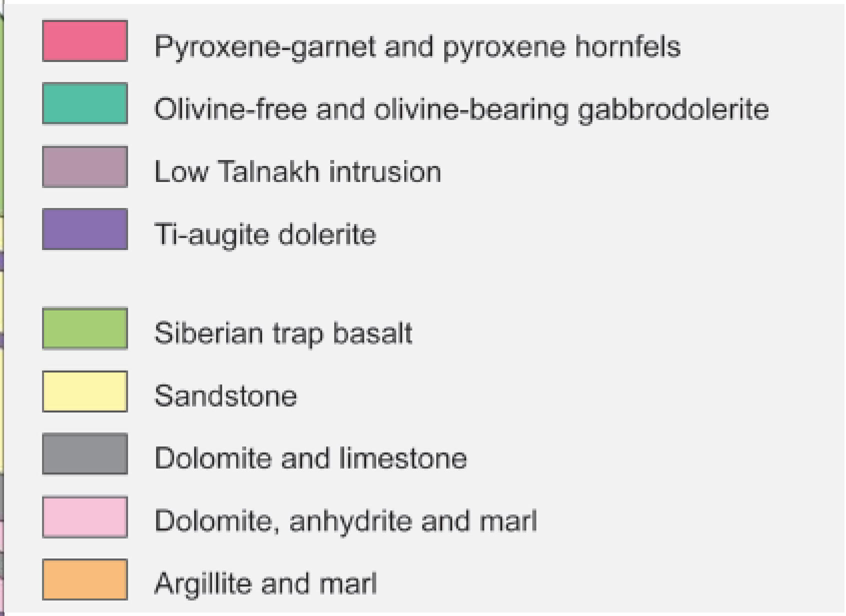
Geological section through the western flank of the Kharaelakh Intrusion



Lightfoot and Zotov (2006)

Geological section through the western flank of Kharaelakh Intrusion





Lightfoot and Zotov (2014)

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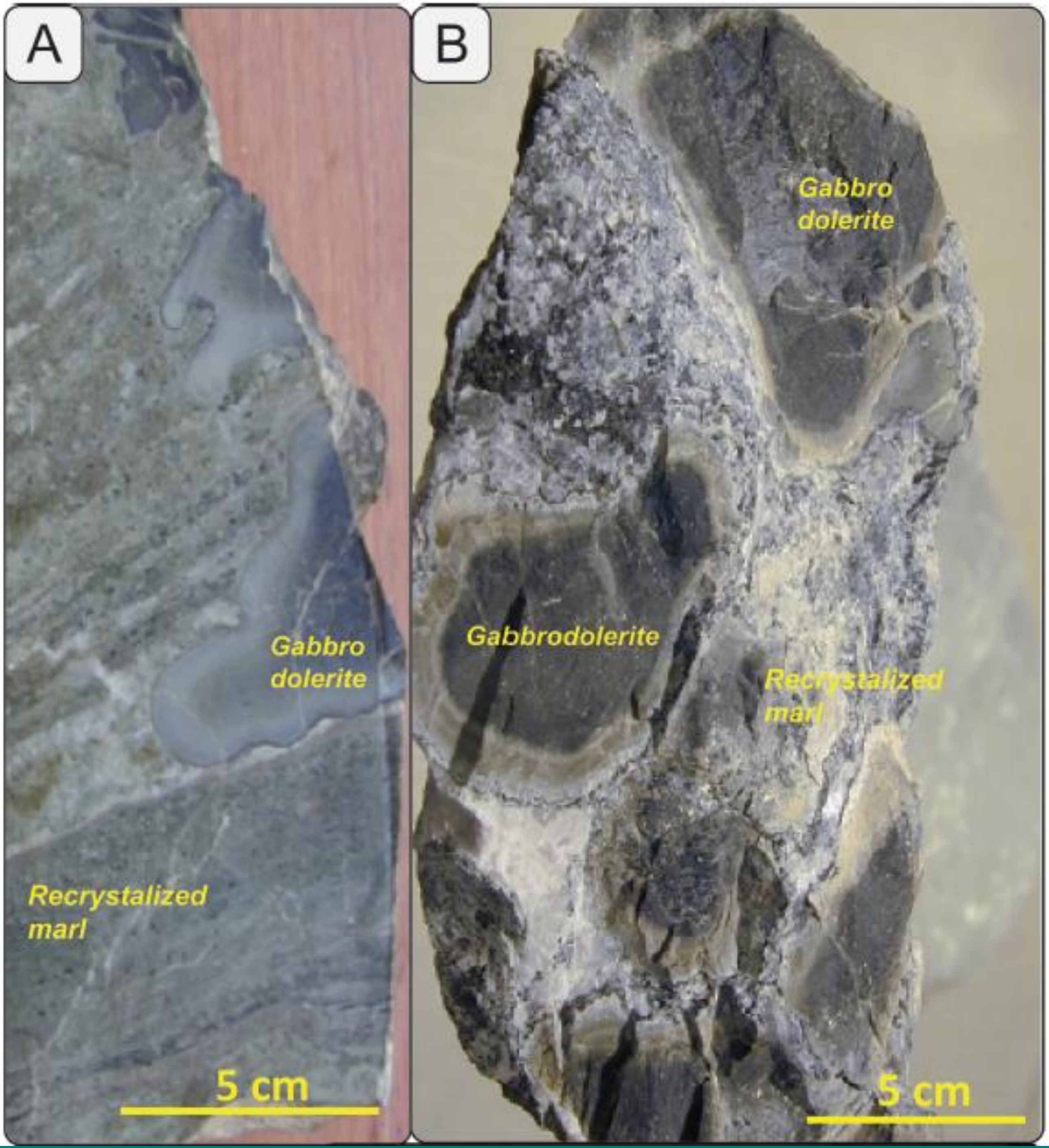
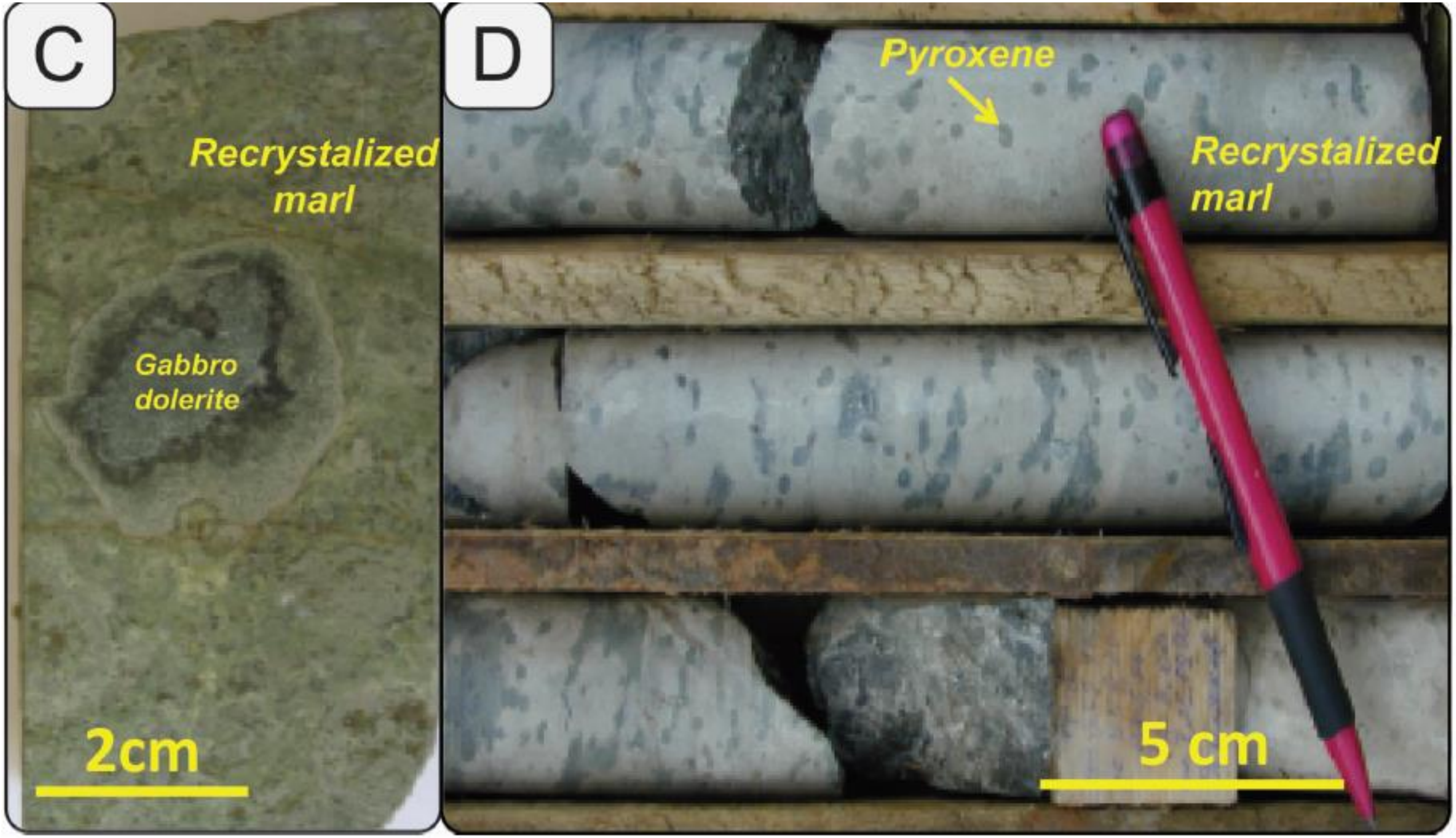
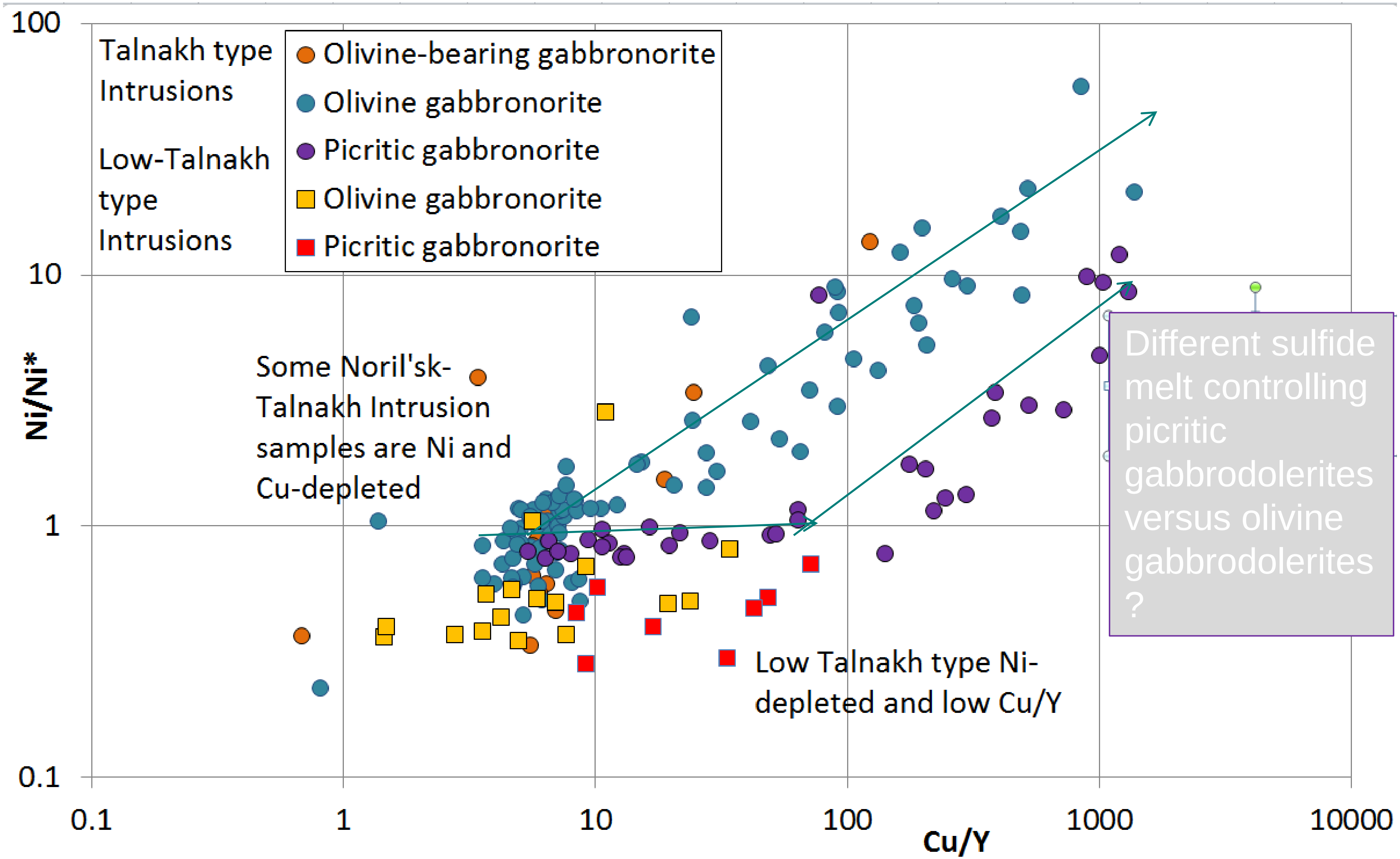
Kharaelakh Intrusion: Apophyses of Chilled Gabbrodolerite in recrystallized marl



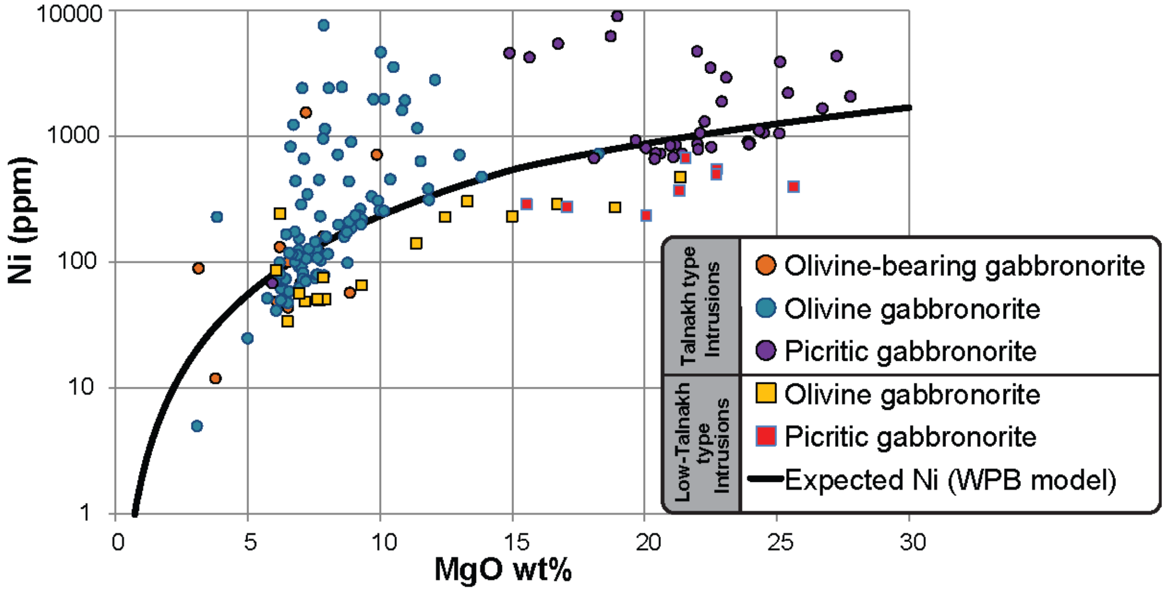
Kharaelakh Intrusion recrystallized marl; spotted hornfels (952m; Drill Core TG21)

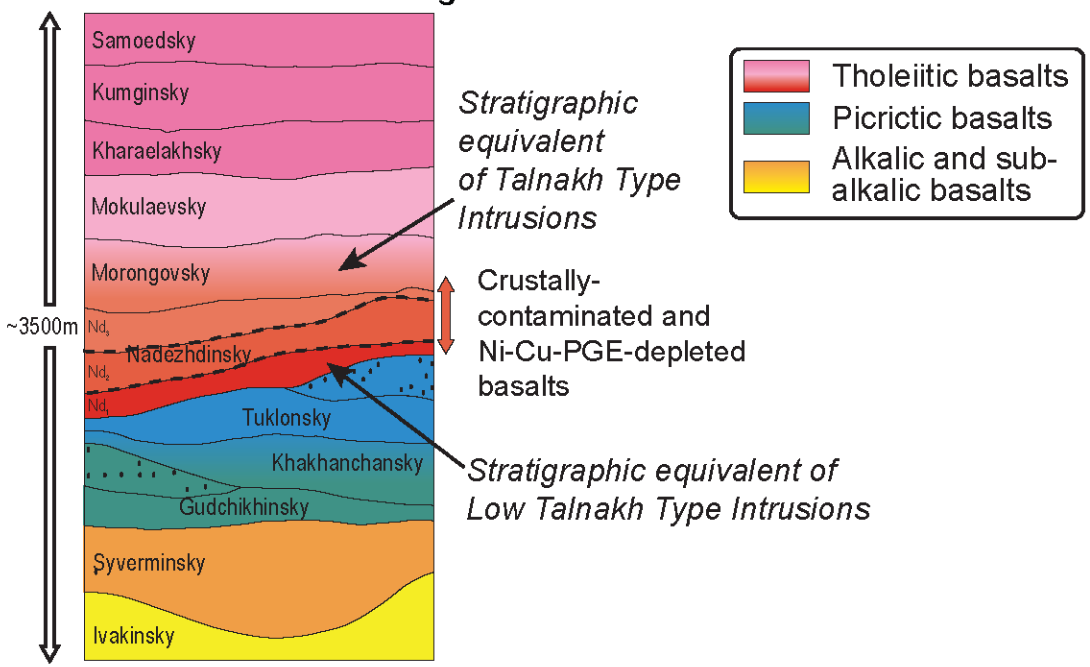


Talnakh Type and Low Talnakh Type Intrusions: La/Sm (contamination index) versus Ni/Ni* (sulfide control index)

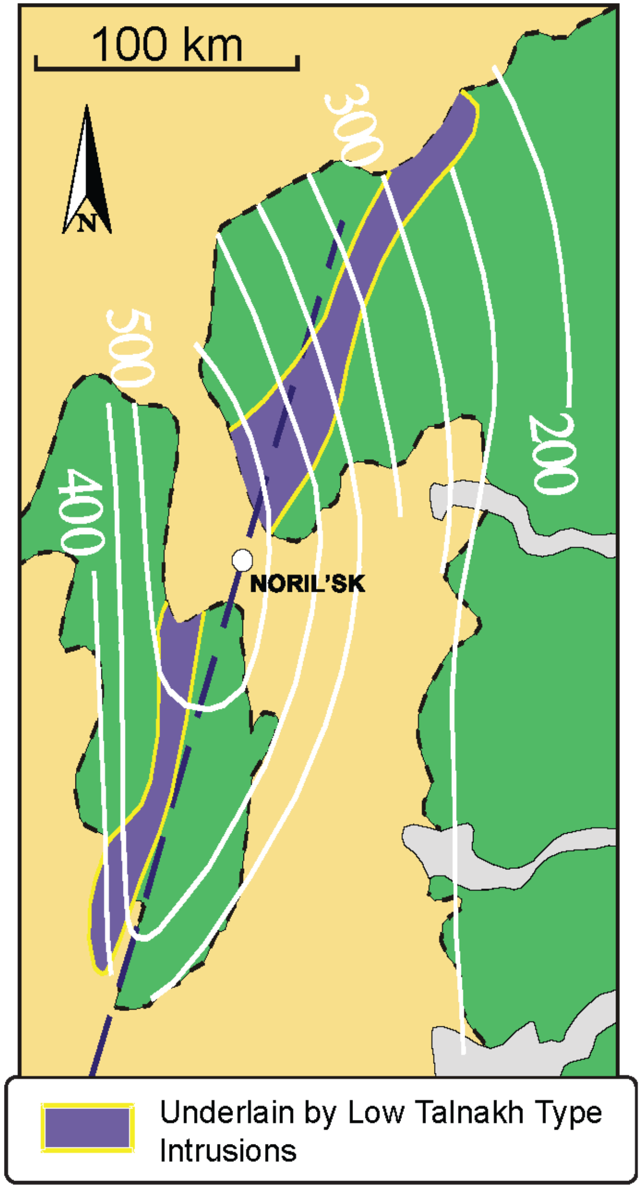


Low Talnakh Type Intrusions are Ni-depleted Relative to Talnakh Type and WPB

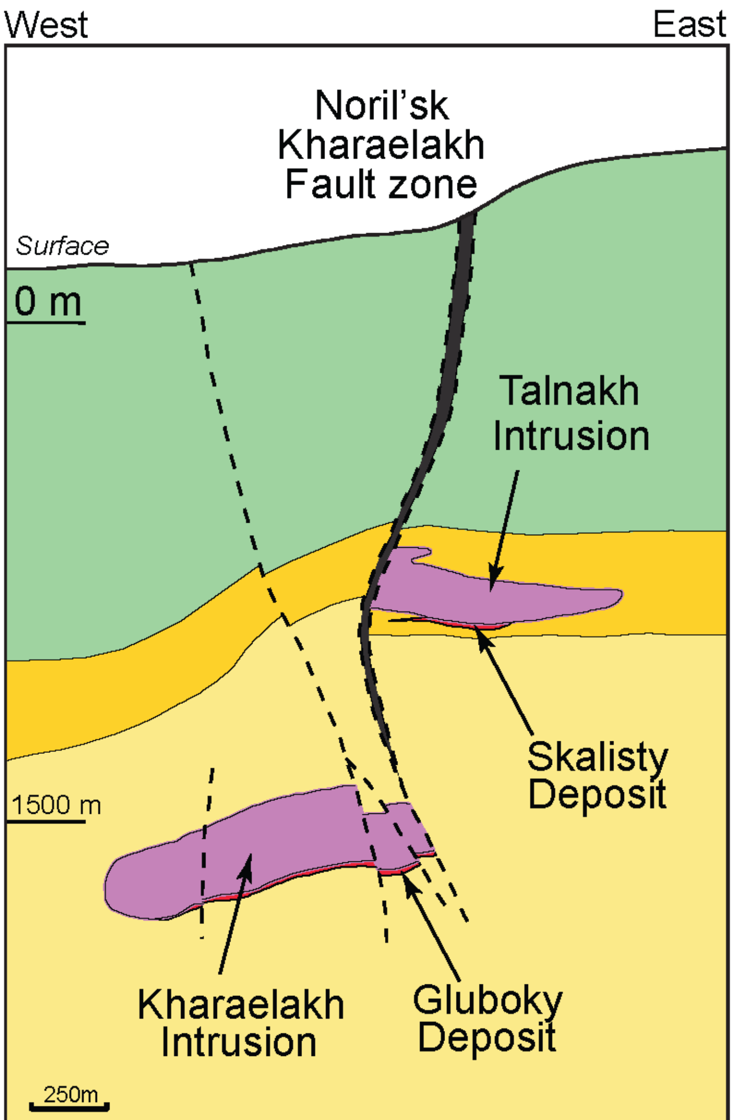




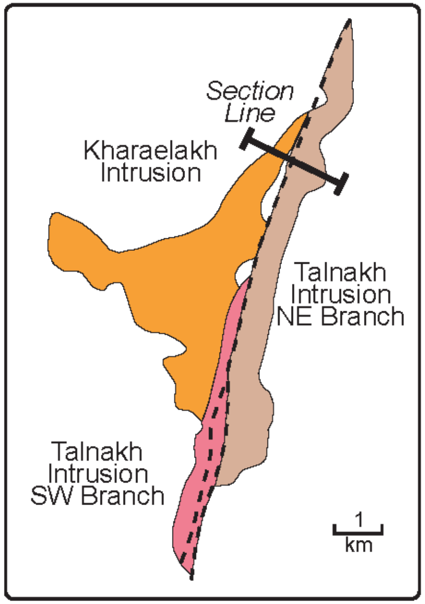
Isopachs (thickness) of Ni - Cu - PGE - depleted basalts of Nd

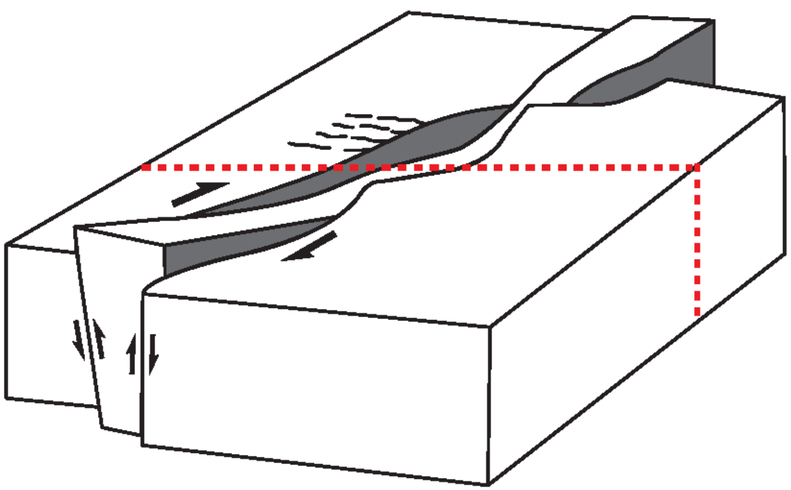


Skalisty and Gluboky Mines, Talnakh and Kharaelakh Intrusion:
North-facing Section



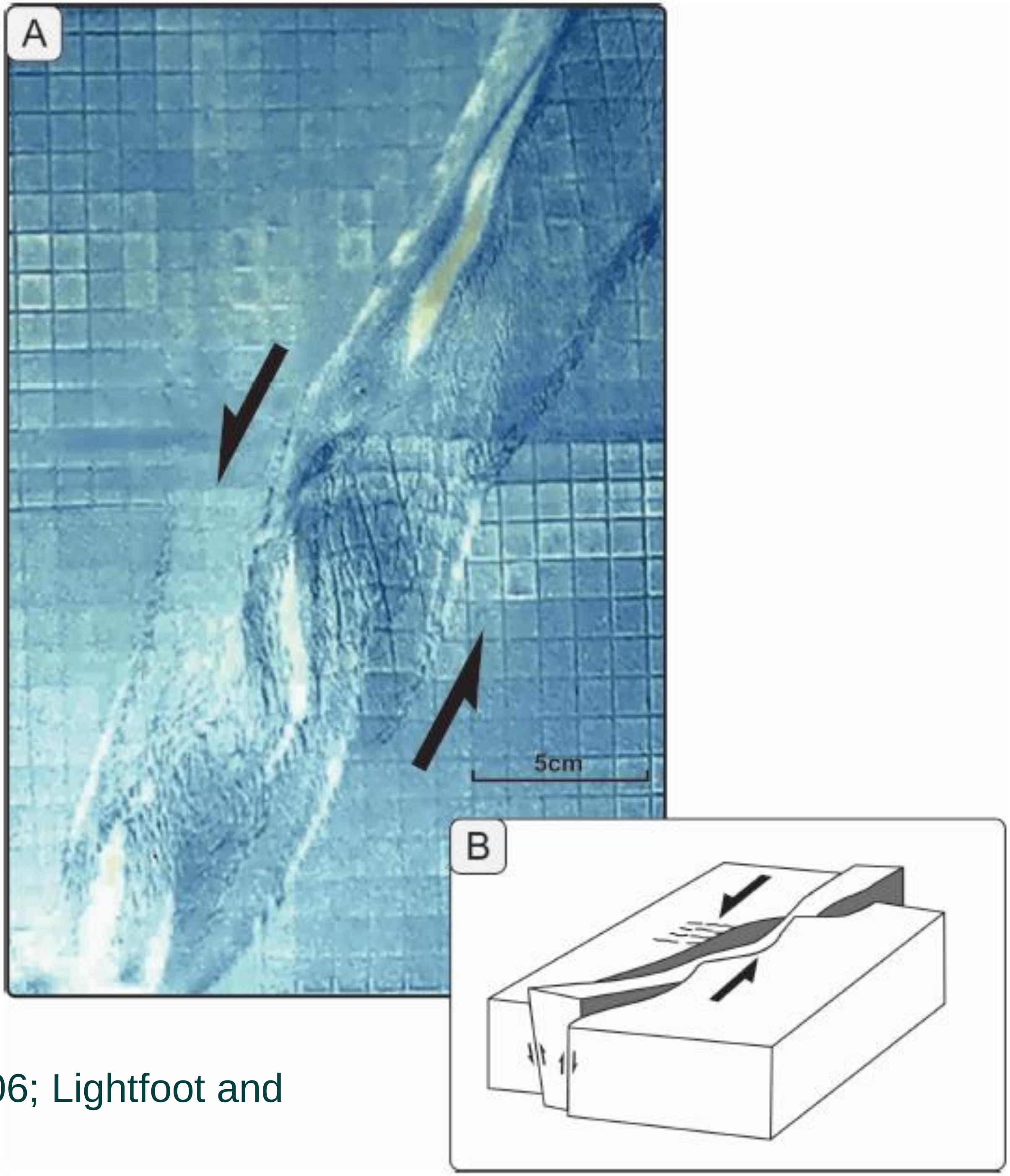
- Siberian Trap basalt
- Carboniferous and Permian sedimentary rocks
- Devonian sedimentary rocks
- Intrusions
- Ni-rich sulphide
- Fault zone





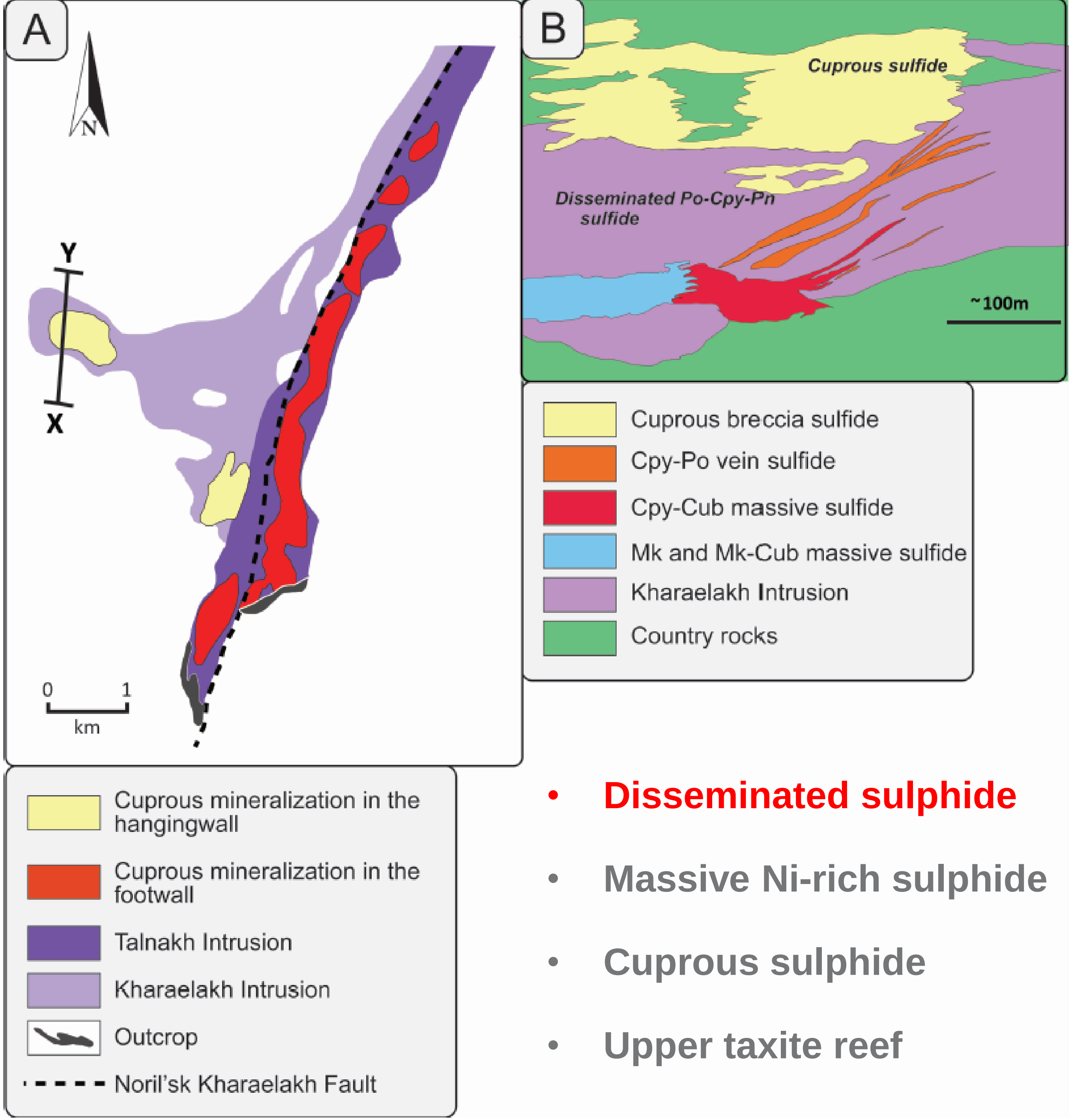
Lightfoot and Evans-Lamswood (2014)

Process of space-creating along mantle-penetrating transform faults



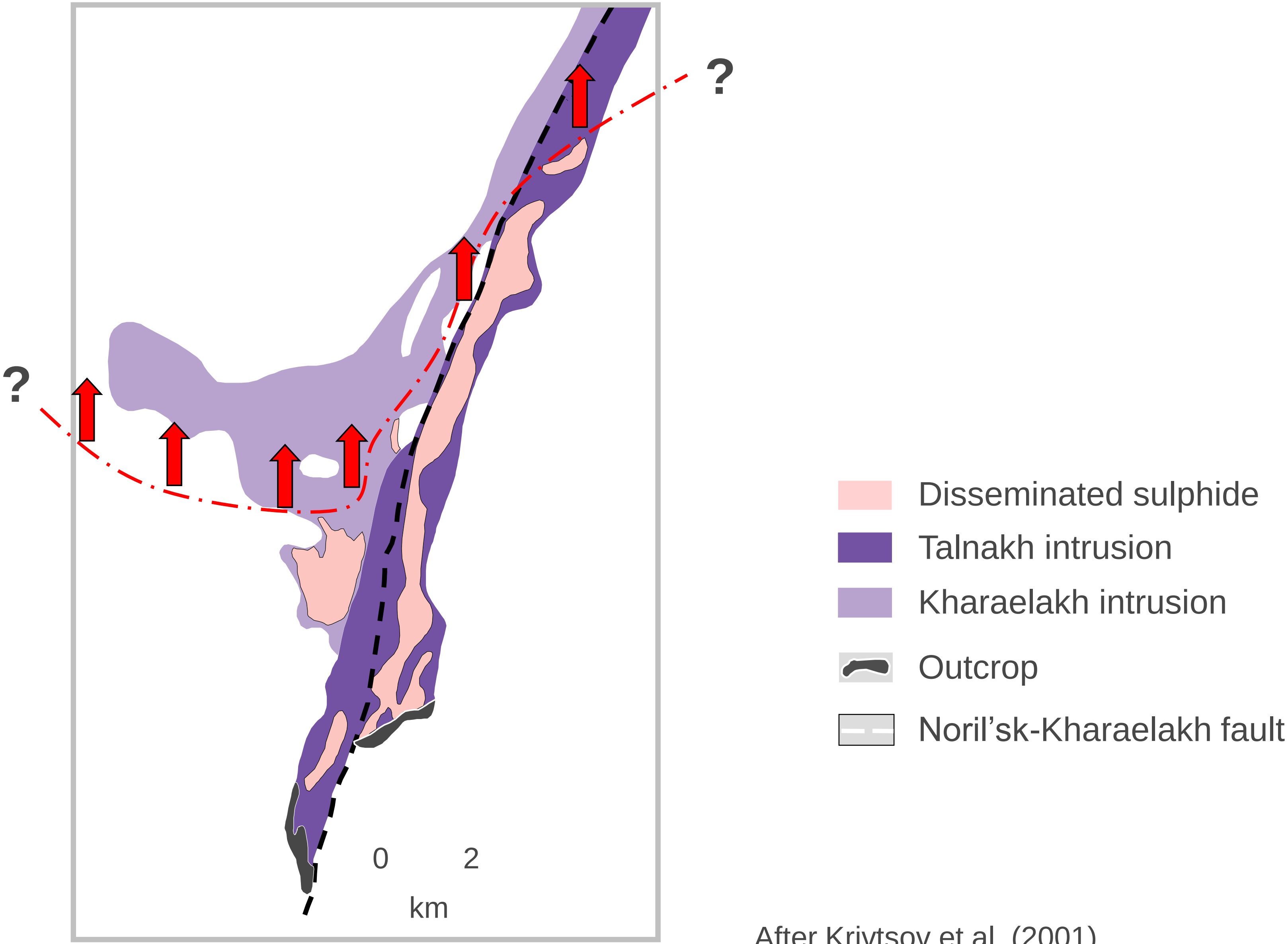
Monteiro and Lightfoot, 2006; Lightfoot and Evans-Lamswood, 2016

Principal ore types at Kharaelakh and Talnakh



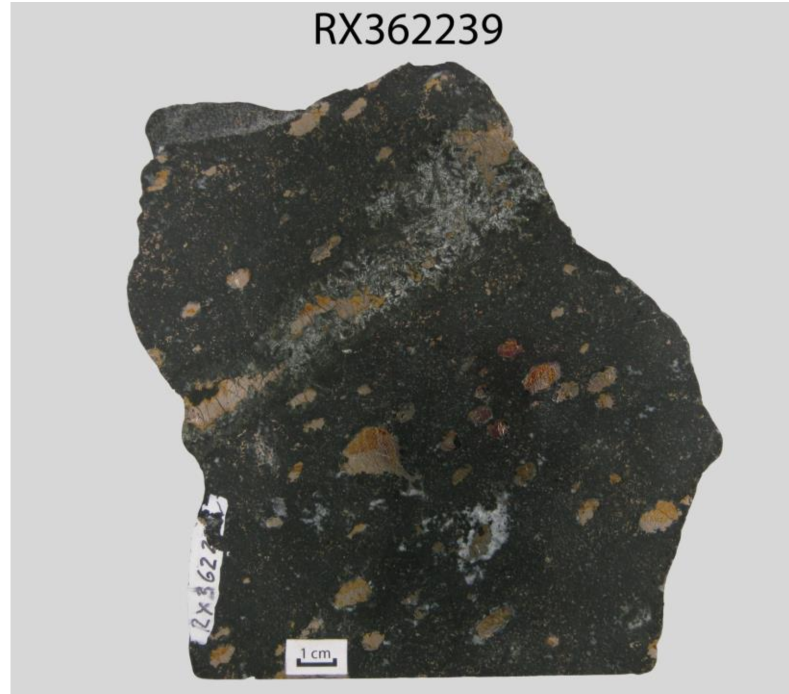
- **Disseminated sulphide**
- **Massive Ni-rich sulphide**
- **Cuprous sulphide**
- **Upper taxite reef**

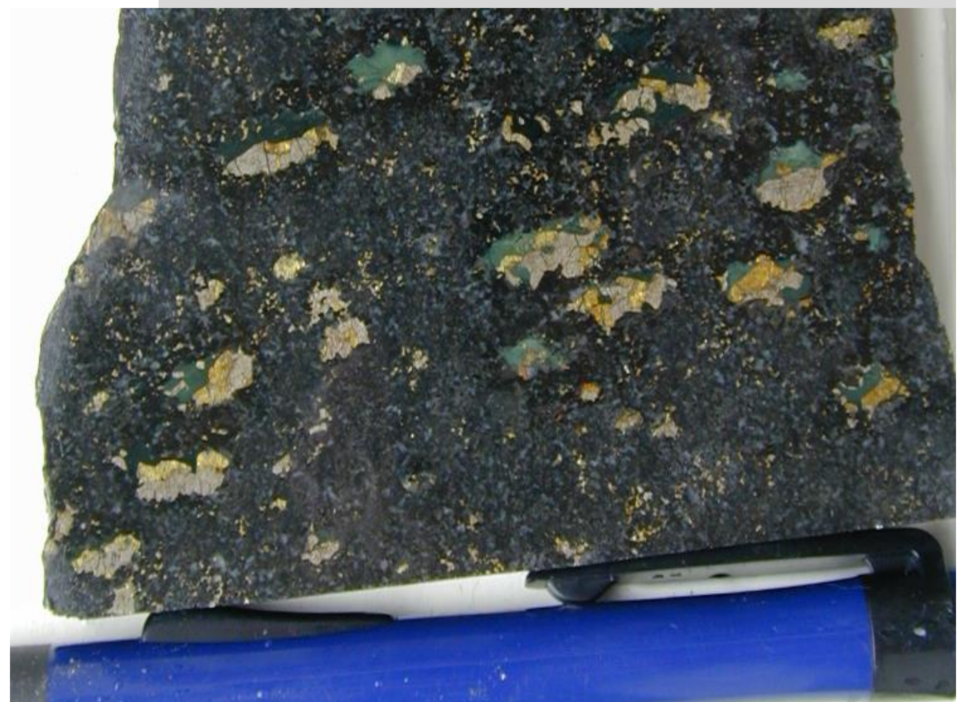
Disseminated Sulphide: distribution at Talnakh and Kharaelakh

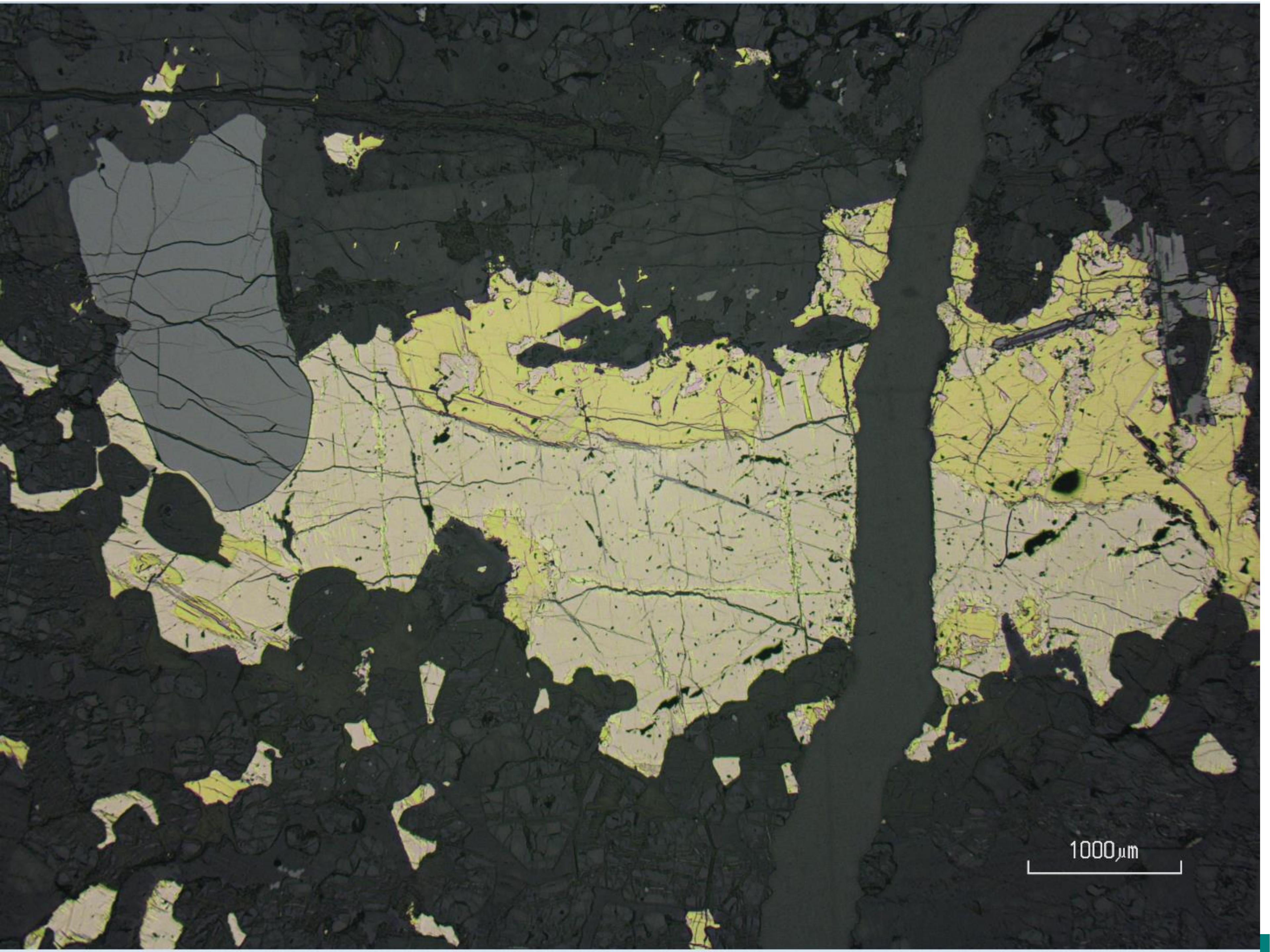


After Krivtsov et al. (2001)

Taxitic gabbrodolerite – Oktyabrysk Mine (Kharaelakh Intrusion)





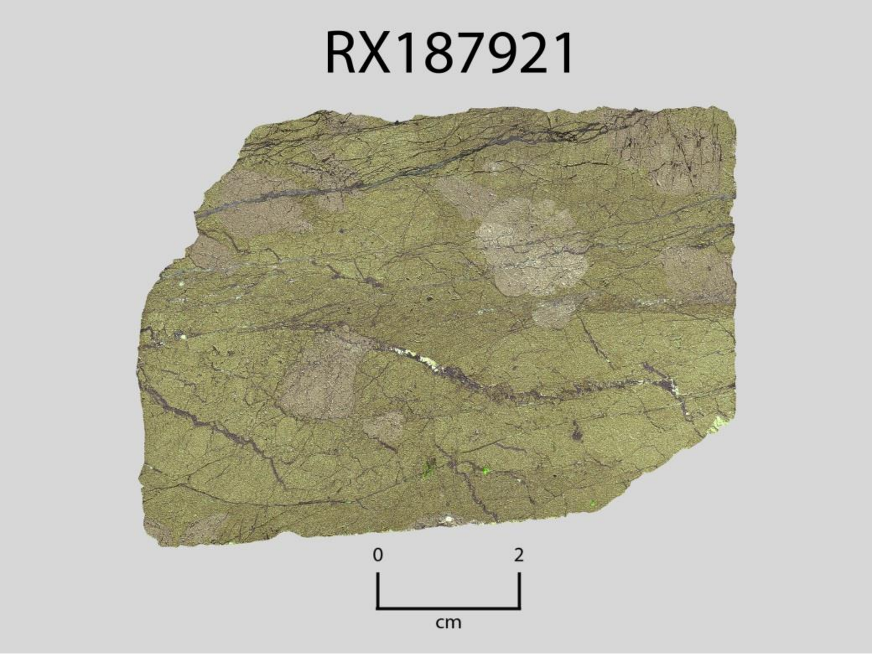

1000µm

Disseminated sulfide ores

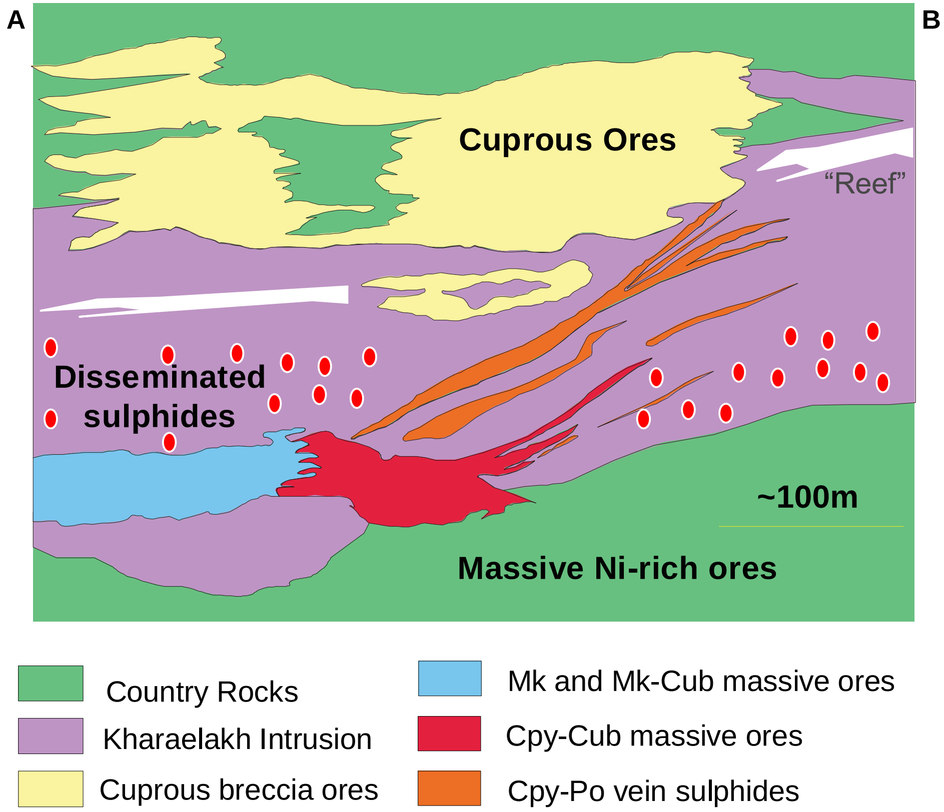
Field Number	8023
RX number	200525
PTS number	C02-0049
Sampled by	PCL (1989)
Intrusion	Oktyabrsky 1 shaft; Oktyabrsky Intrusion
Rock type	Taxitic hypidiomorphic-textured mela augite troctolite.
Mineralogy	This specimen has a fairly pristine pyrrhotite dominant assemblage with po>>cp>pn with minor cubanite. The usual tiny grains are associated with alteration cracks in olivine.
Mine	Oktyabrsky 1 shaft; Oktyabrsky Intrusion
MgO (wt%)	n.a.
Ni (wt%)	0.96
Cu (wt%)	2.91
Co (wt%)	0.03
S (wt%)	5.13
Pt (ppm)	3.66
Pd (ppm)	11.30
Au (ppm)	0.93

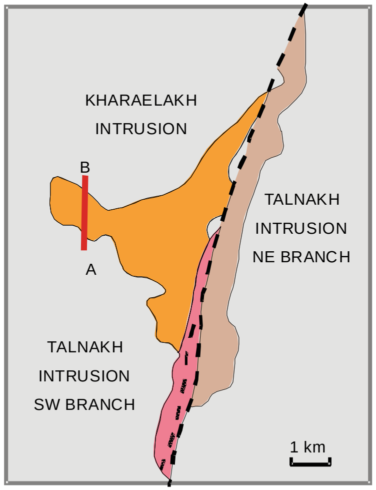
Noril'sk: Medvezhy Ruchei. Picritic gabbro-dolerite with stock-work of sulphide veins – injection of massive sulfide into consolidated intrusion

Field Number	n.a.
RX number	187921
PTS number	n.a.
Sampled by	PCL
Intrusion	Noril'sk I
Rock type	MASU vein cutting Taxitic gabbrodolerite
Mineralogy	Massive cpy-pn-po
Mine	Bears Brook
MgO (wt%)	n.a.
Ni (wt%)	5.51
Cu (wt%)	29.2
Co (wt%)	0.07
S (wt%)	33.2
Pt (ppm)	72.4
Pd (ppm)	334
Au (ppm)	0.53

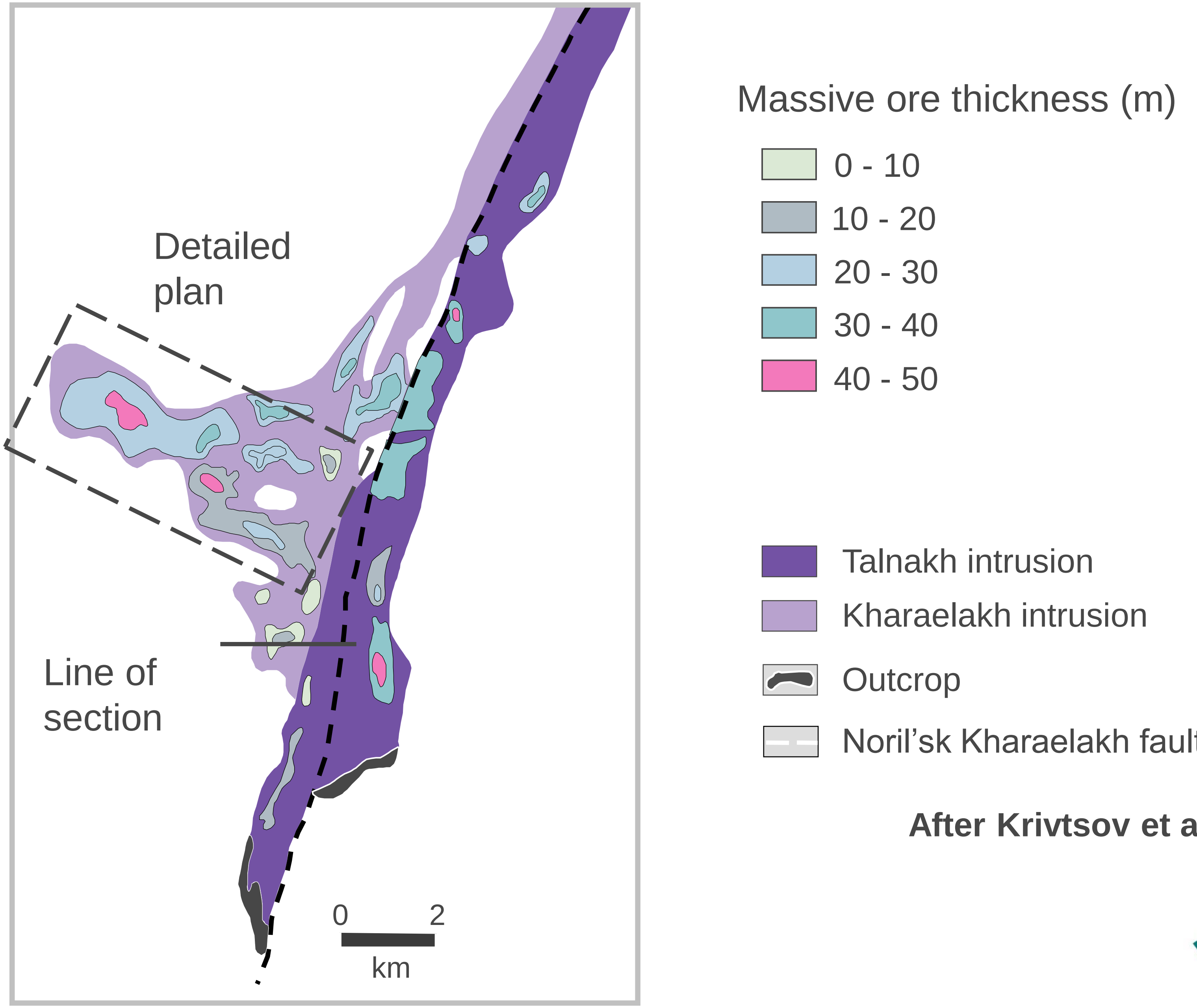


- Disseminated sulphide
- **Massive Ni-rich sulphide**
- Cuprous sulphide
- (Upper taxite reef sulphide)





Massive Ore Thickness – Kharaelakh and Talnakh



After Krivtsov et al. (2001)

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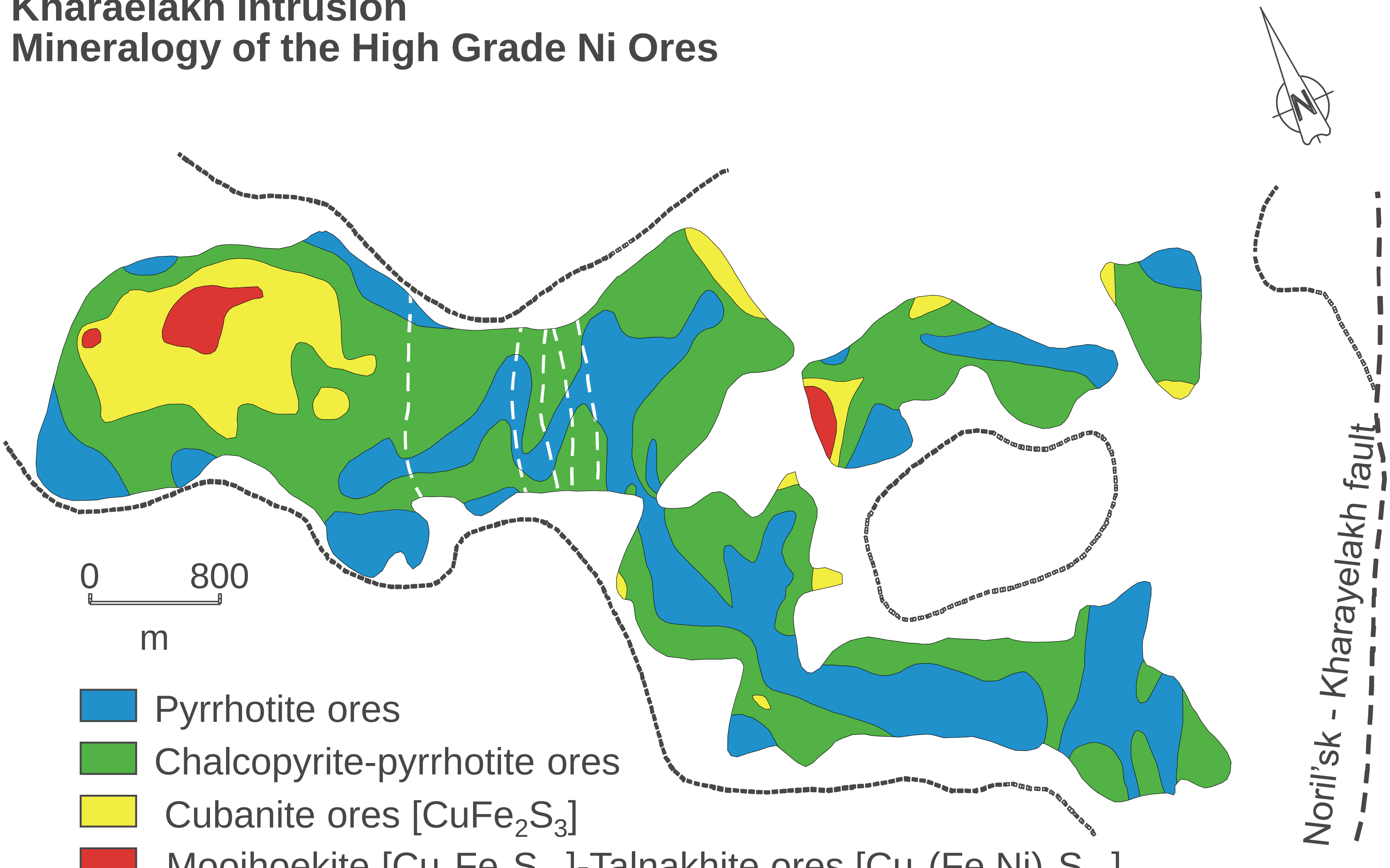
Kharaelakh Intrusion
Mineralogy of the High Grade Ni Ores



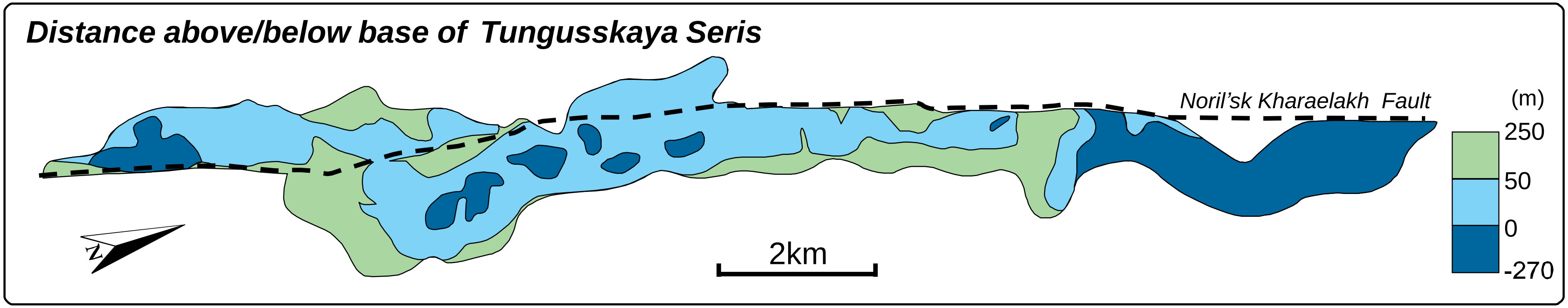
- Pyrrhotite ores
- Chalcopyrite-pyrrhotite ores
- Cubanite ores [$CuFe_2S_3$]
- Mooihoekite [$Cu_9Fe_9S_{16}$]-Talnakhite ores [$Cu_9(Fe,Ni)_8S_{16}$]
- Faults
- Outline of intrusion

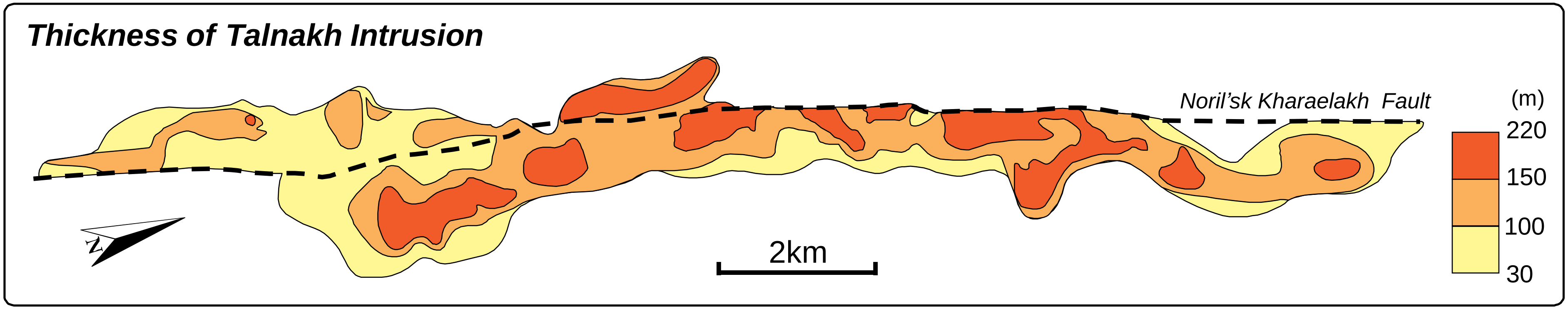
Pentlandite is present in all ore types

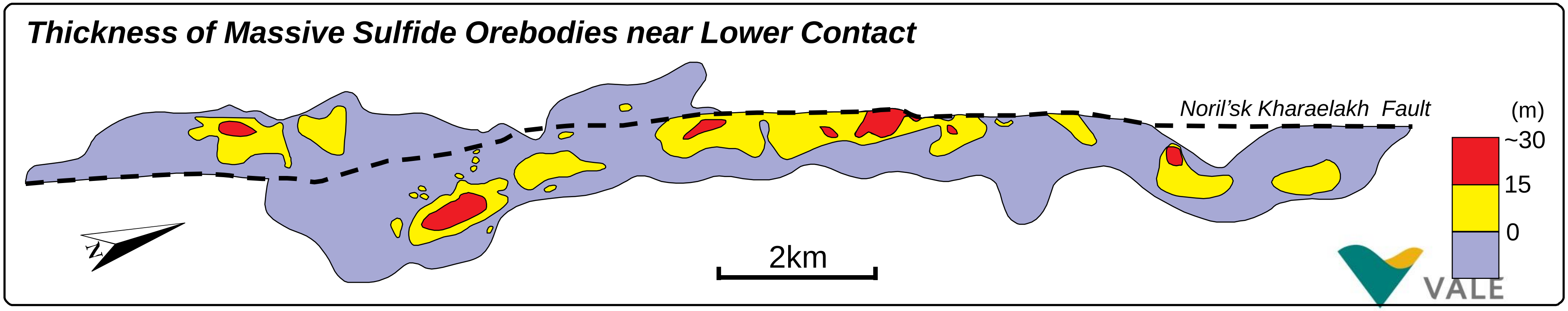
Stekhin (1994)

VALE

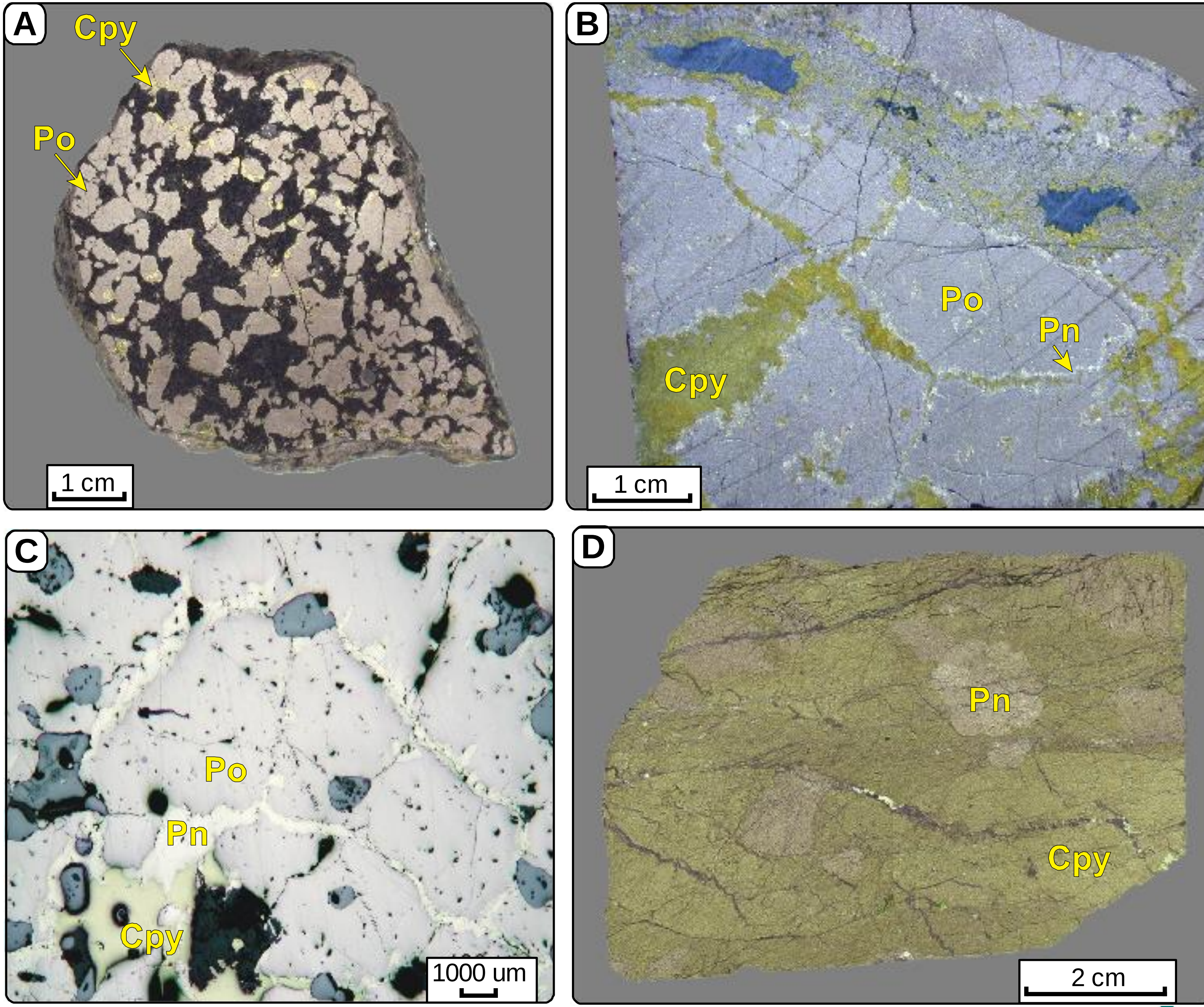
Geological Relationships between the Talnak Intrusion, the orebodies and the country rocks





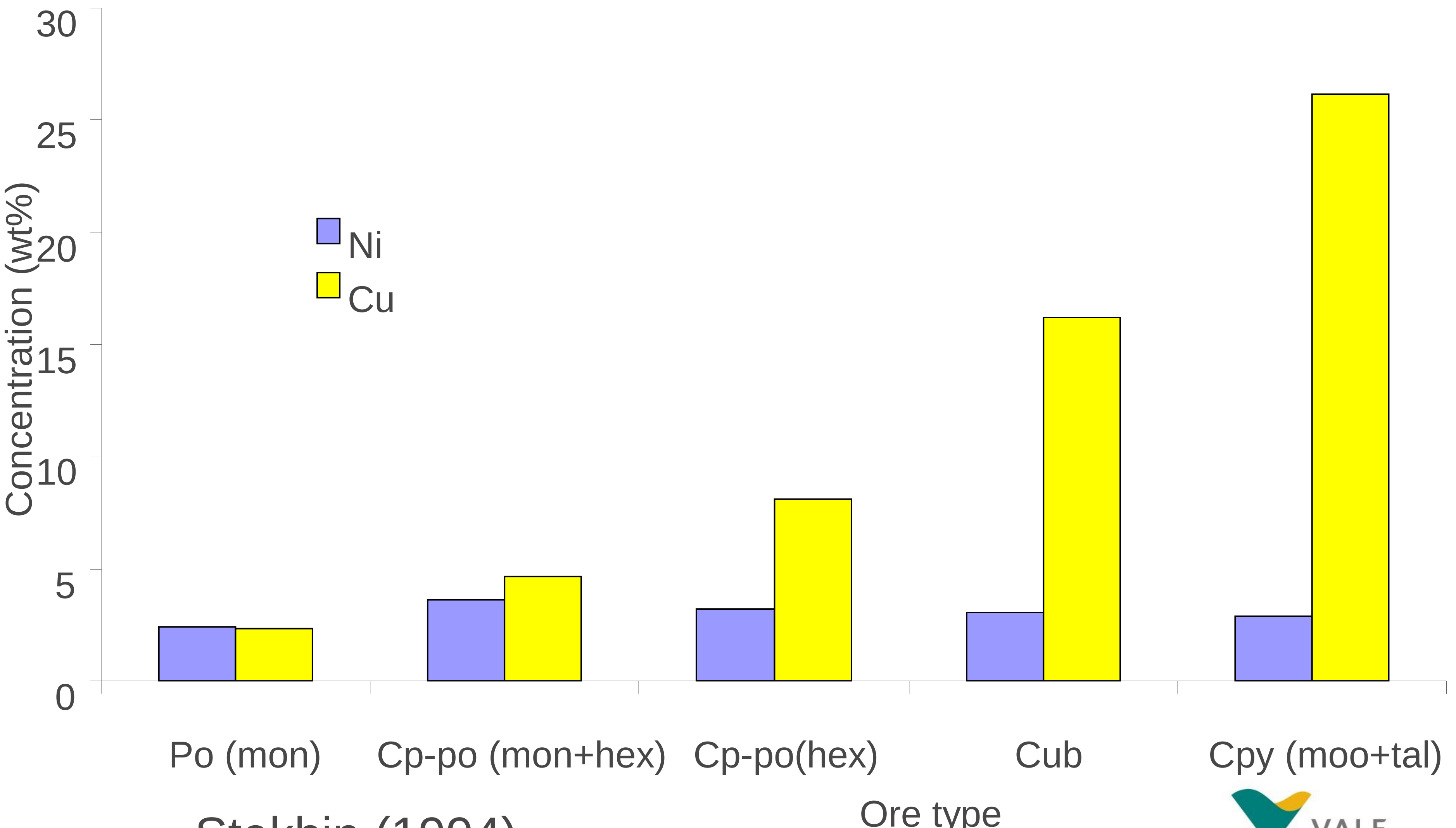


Skalisty Mine, Talnakh Intrusion: MASU cutting footwall shales of Tungusskaya Series – typical of massive Ni-rich sulfides



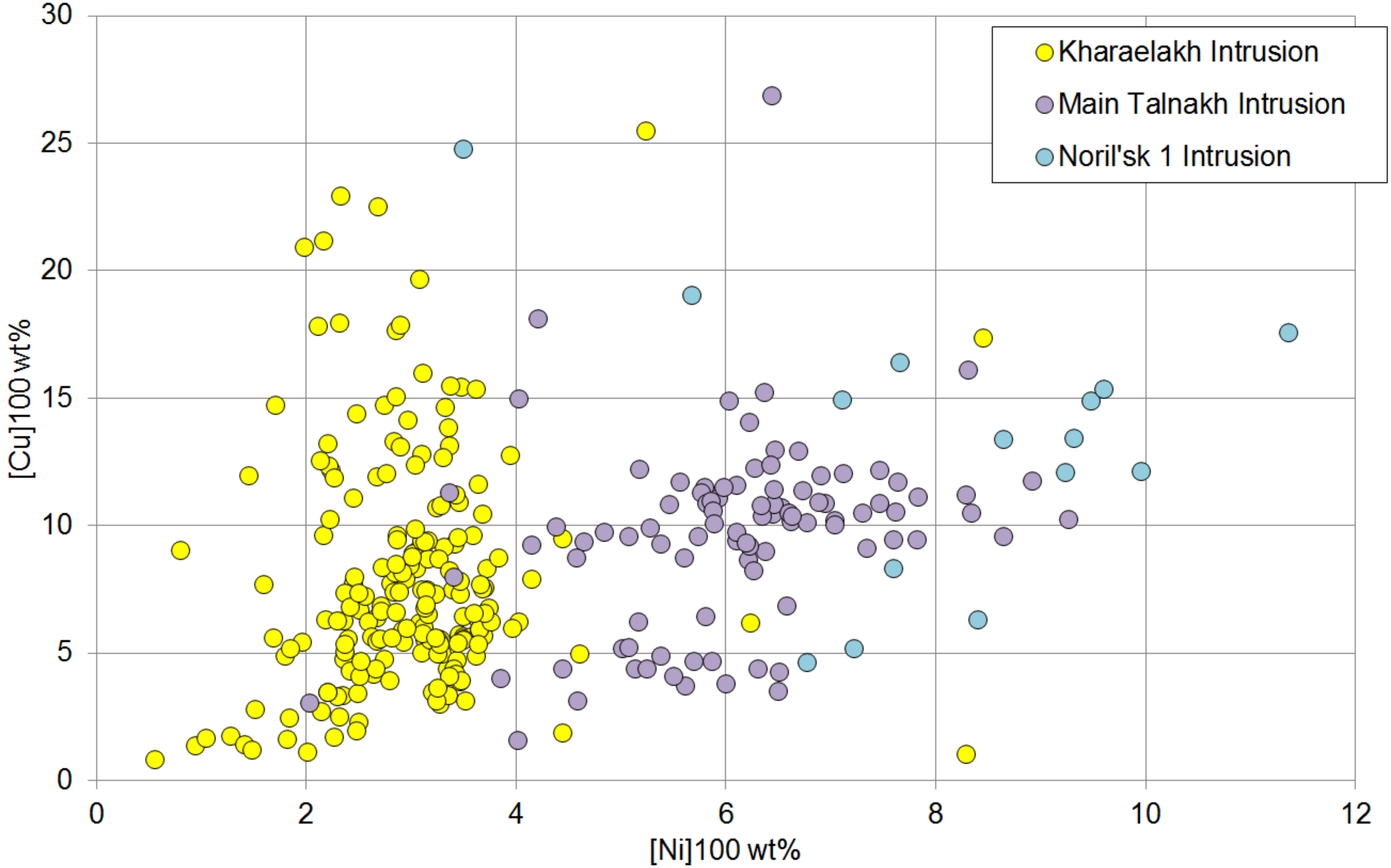
Lightfoot, 2016

Talnakh and Oktyabrsk Deposits
Concentrations of Ni and Cu in different Ni-rich ore types



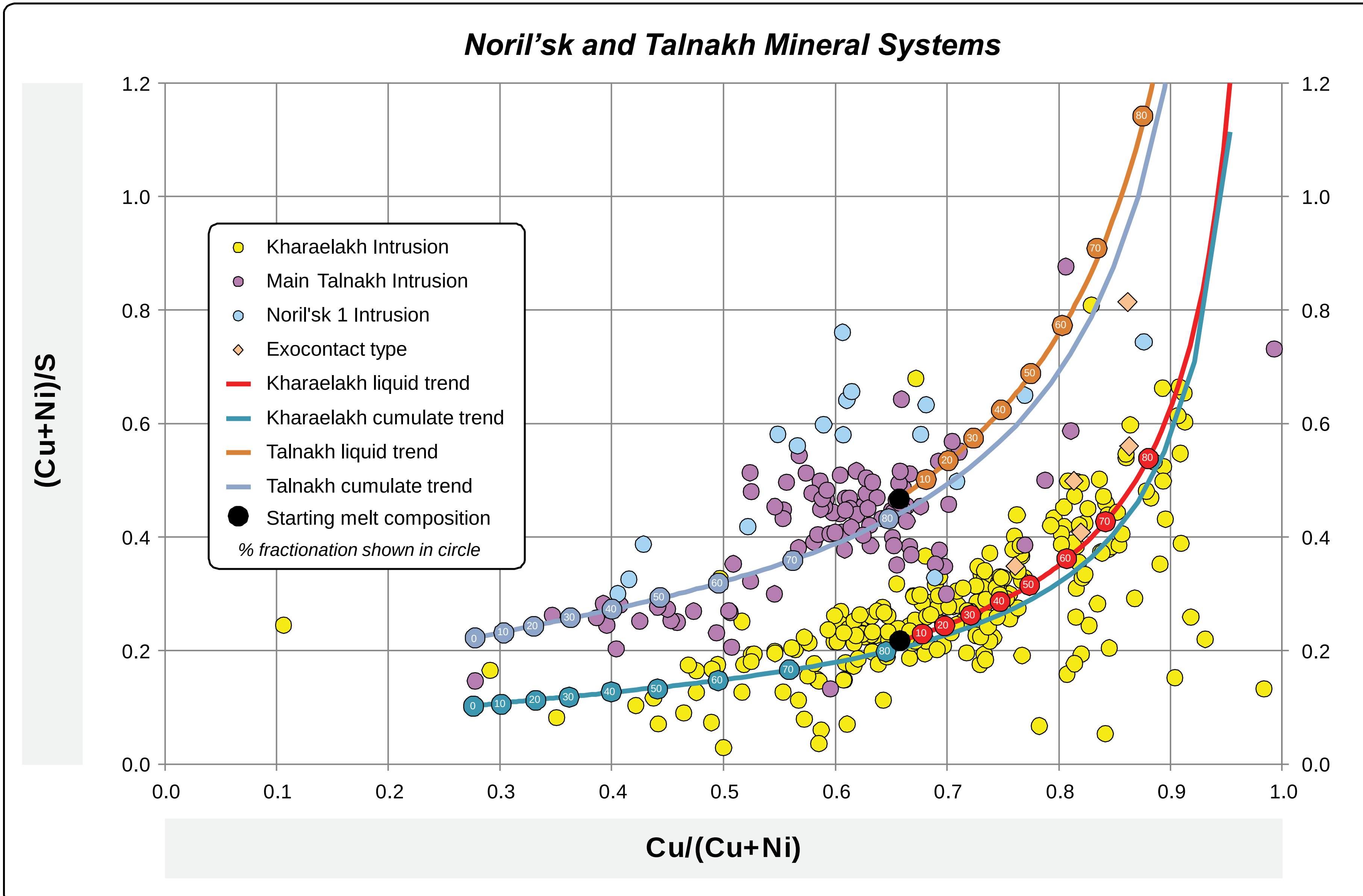
Stekhin (1994)

Ni tenor of sulfides from Noril’sk, Talnakh, and Kharaelakh



Modified from Lightfoot (2016)

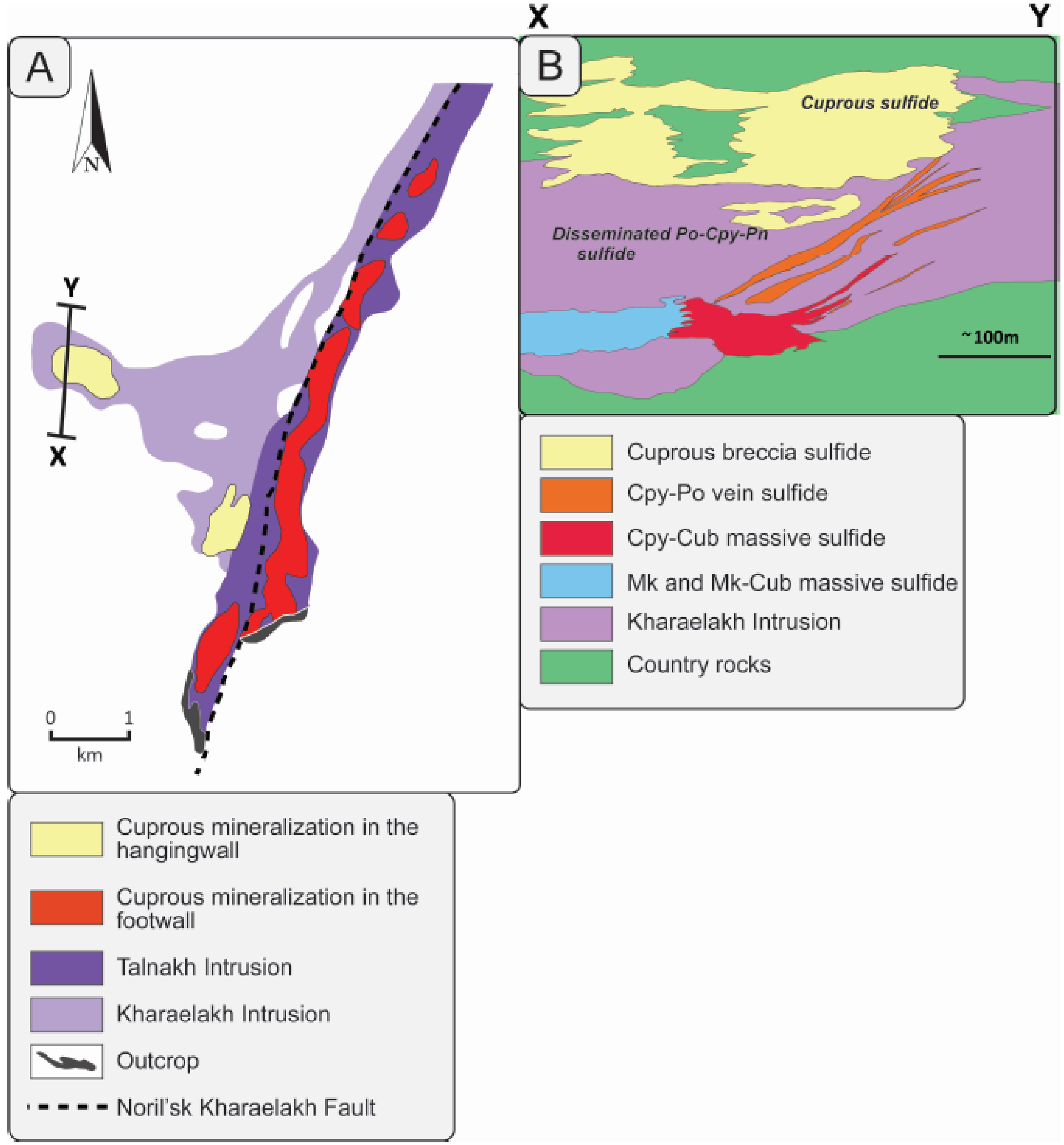
Geochemistry of the Noril'sk ores



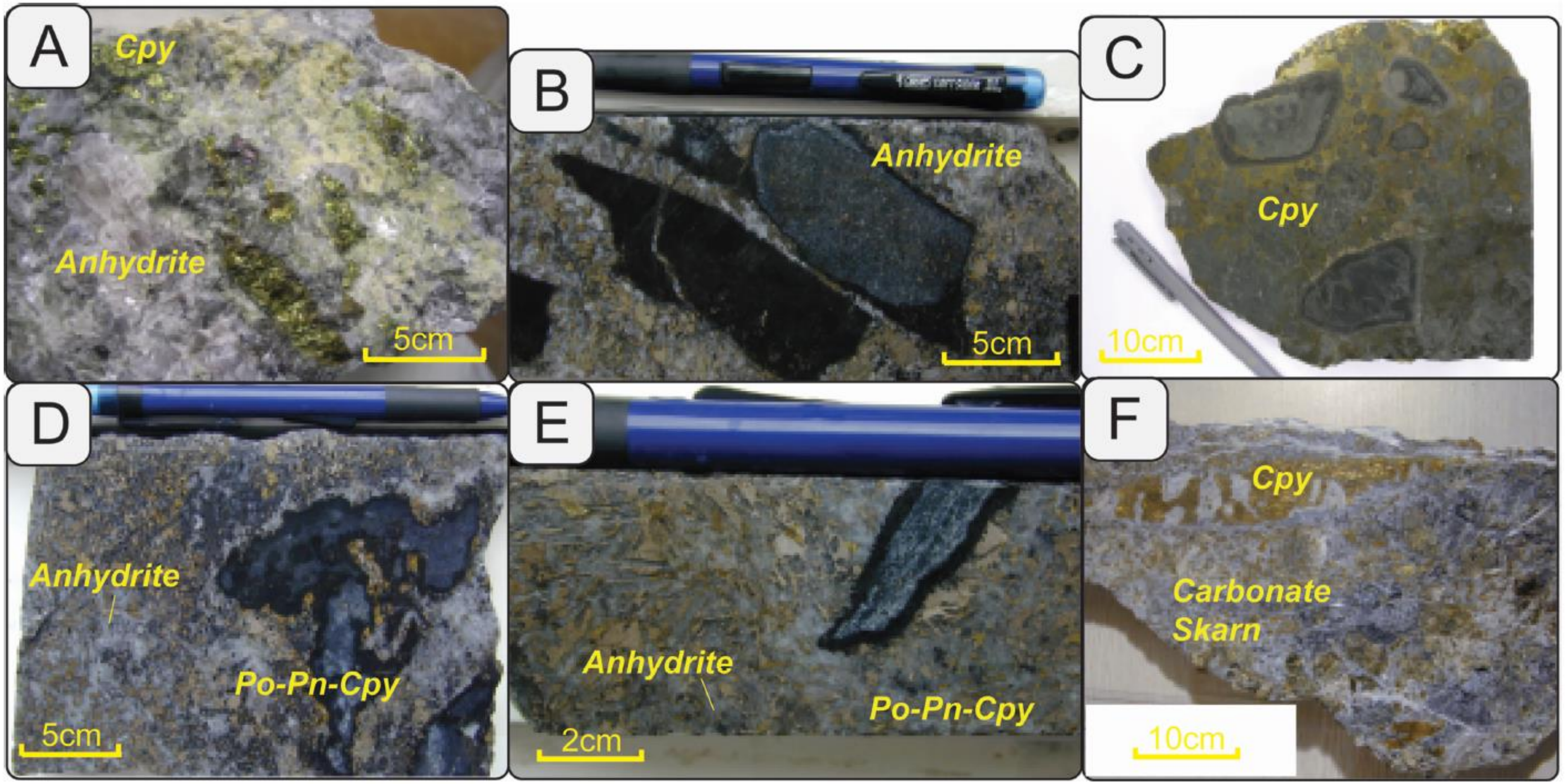
Lightfoot, 2016

Principal ore types at Talnakh

- Disseminated sulphide
- Massive Ni-rich sulphide
- Cuprous sulphide
- Upper taxite reef



Cuprous Ores
Oktyabrysk Deposit



Lightfoot and Zotov, 2013

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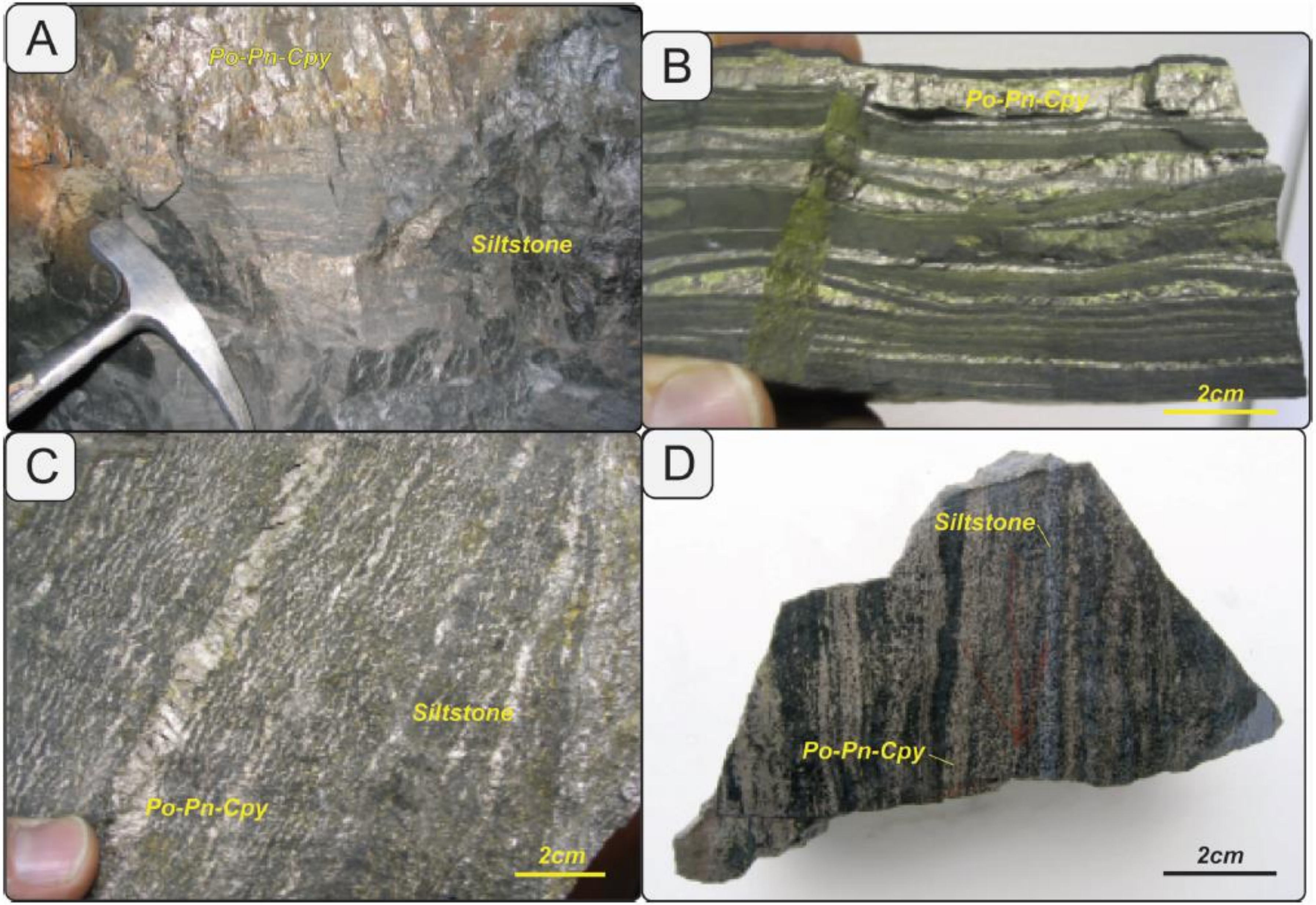
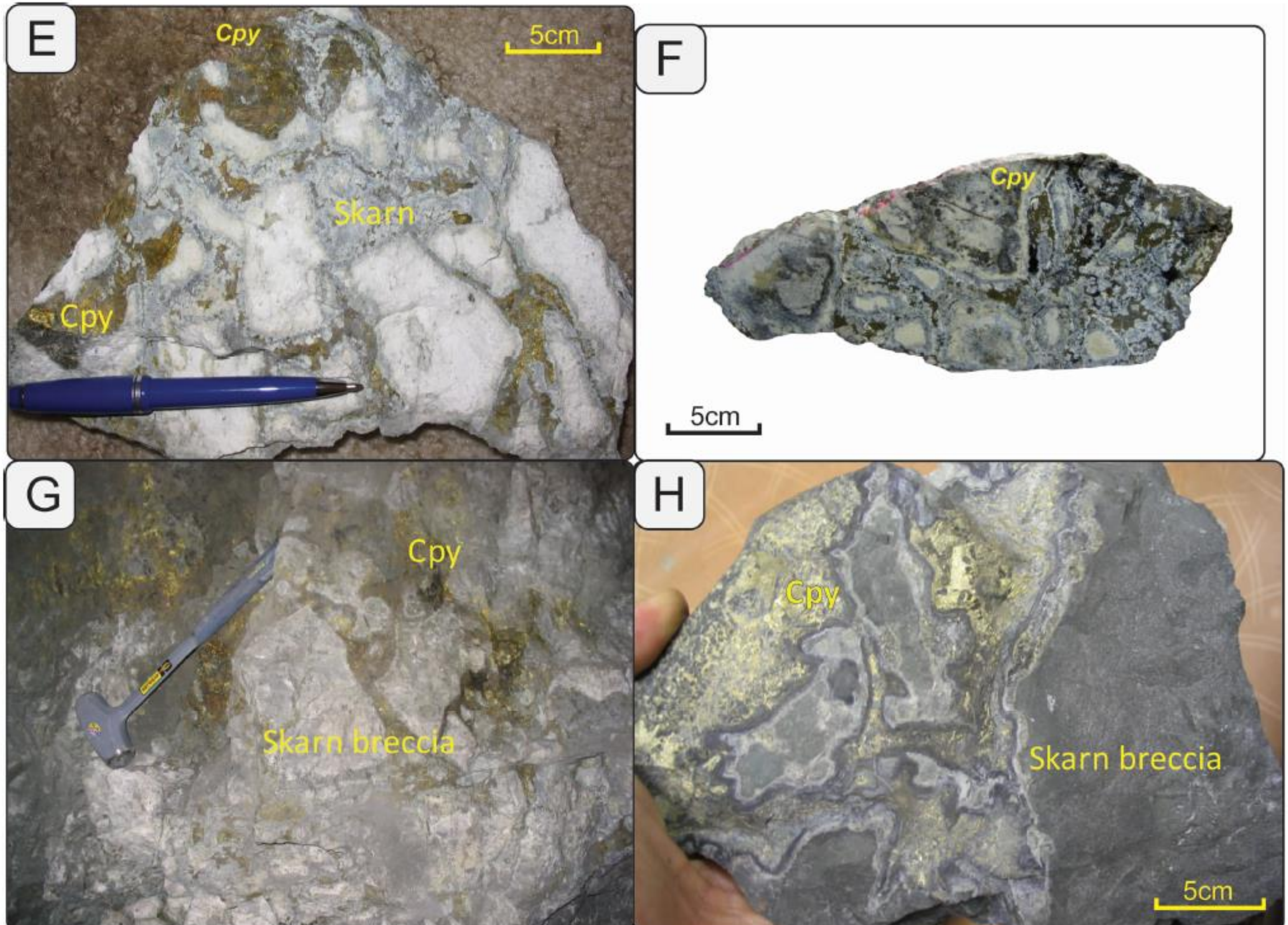
Talnakh Intrusion: Skalisty Mine. Cuprous Ore along bedding in footwall hornfels



Lightfoot and Zotov, 2013

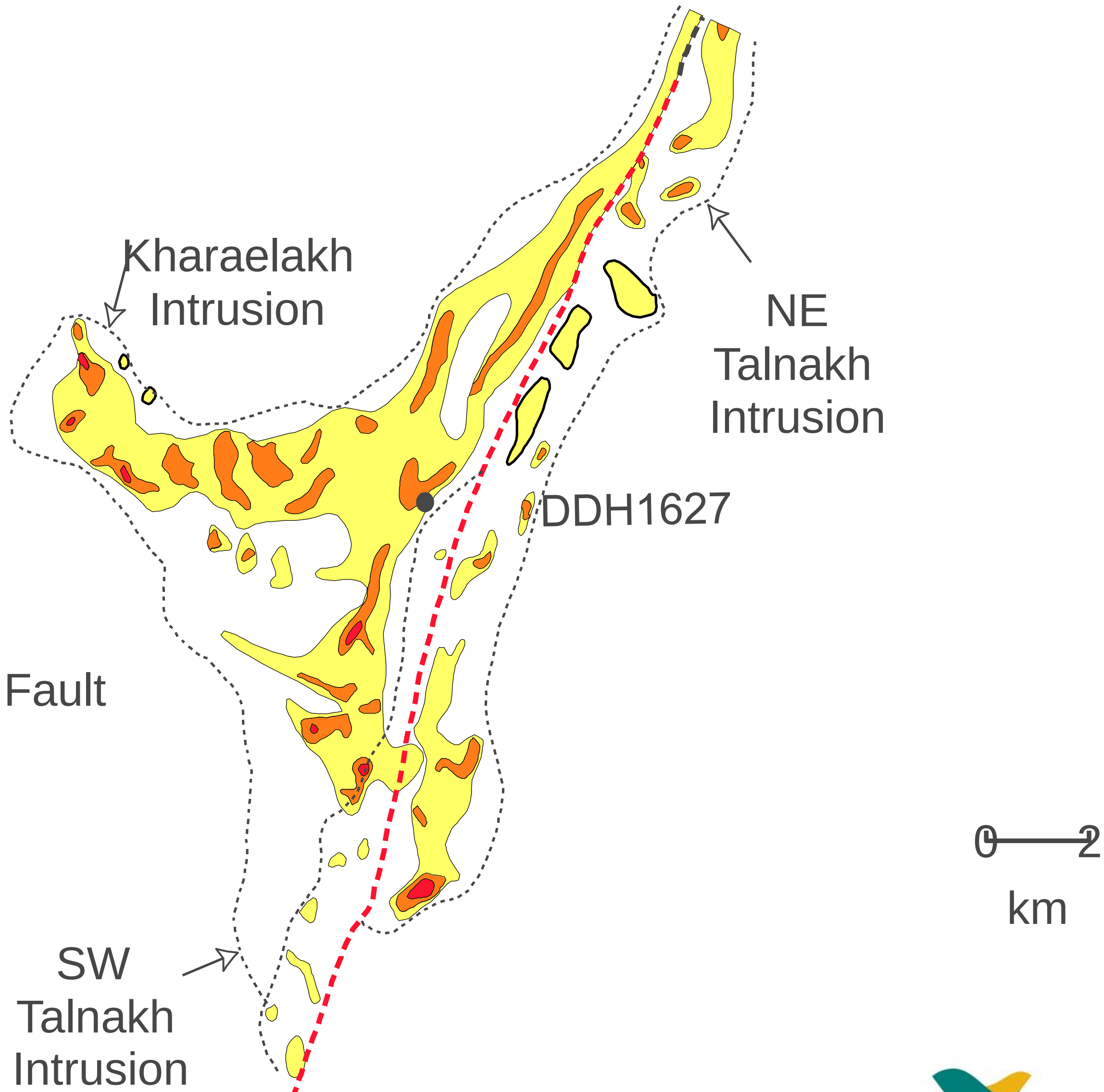
Cuprous ore – developed in footwall of Skalisty Mine



Lightfoot and Zotov, 2013

Talnakh
Distribution of Gabbroids with Low-Sulphide PGE Mineralisation

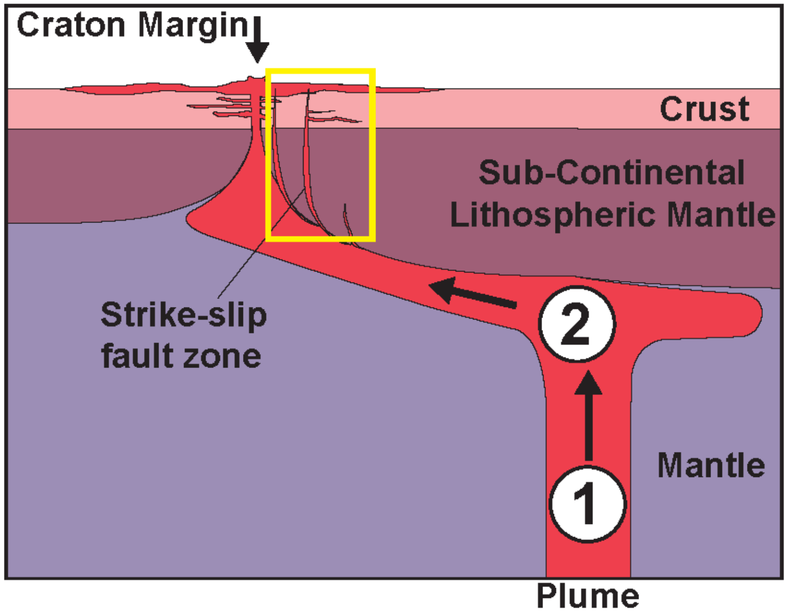
- Disseminated sulphide
- Massive Ni-rich sulphide
- Cuprous sulphide
- (Upper taxite reef sulphide)



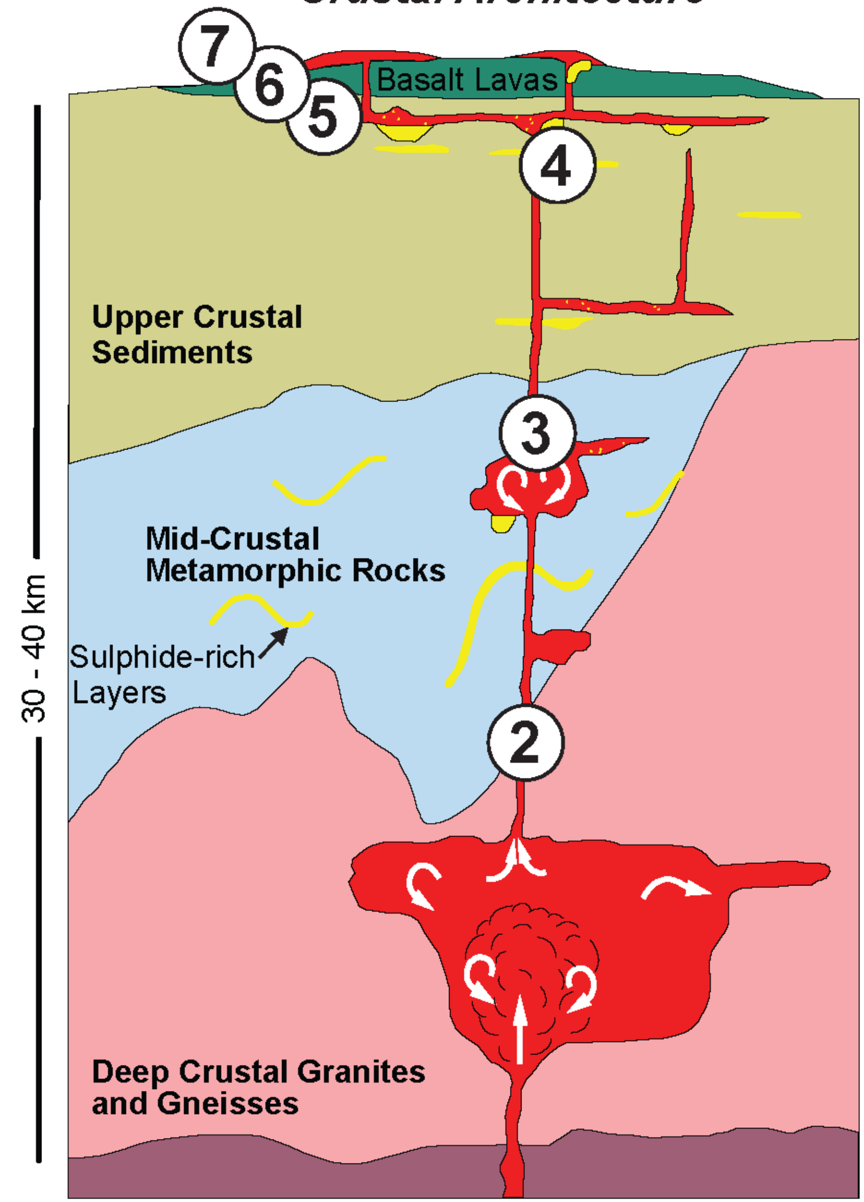
Process Controls on Formation of Nickel Sulfides

VALE

Tetonic Setting



Crustal Architecture



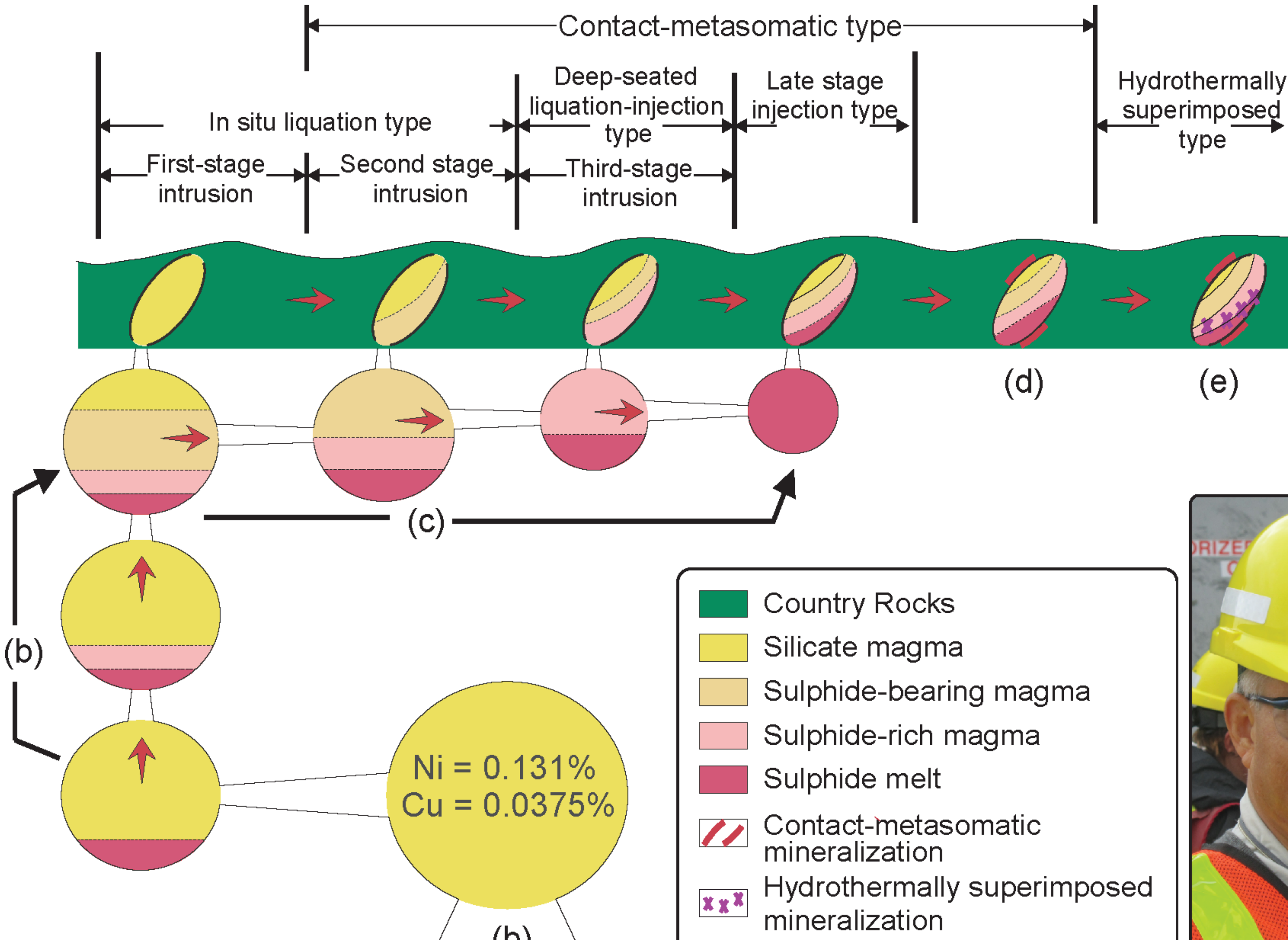
After: Lightfoot (2007), Naldrett (2010) and Begg et al (2011)

Key Process Controls

7. Syn-tectonic and post-tectonic modification
6. Sulphide segregation and fractionation
5. Sulphide saturation and metal-endowment
4. Emplacement
3. Fractionation and contamination
2. Ascent of magma
1. Generate ultramafic magma from metal-endowed source

Jinchuan Model

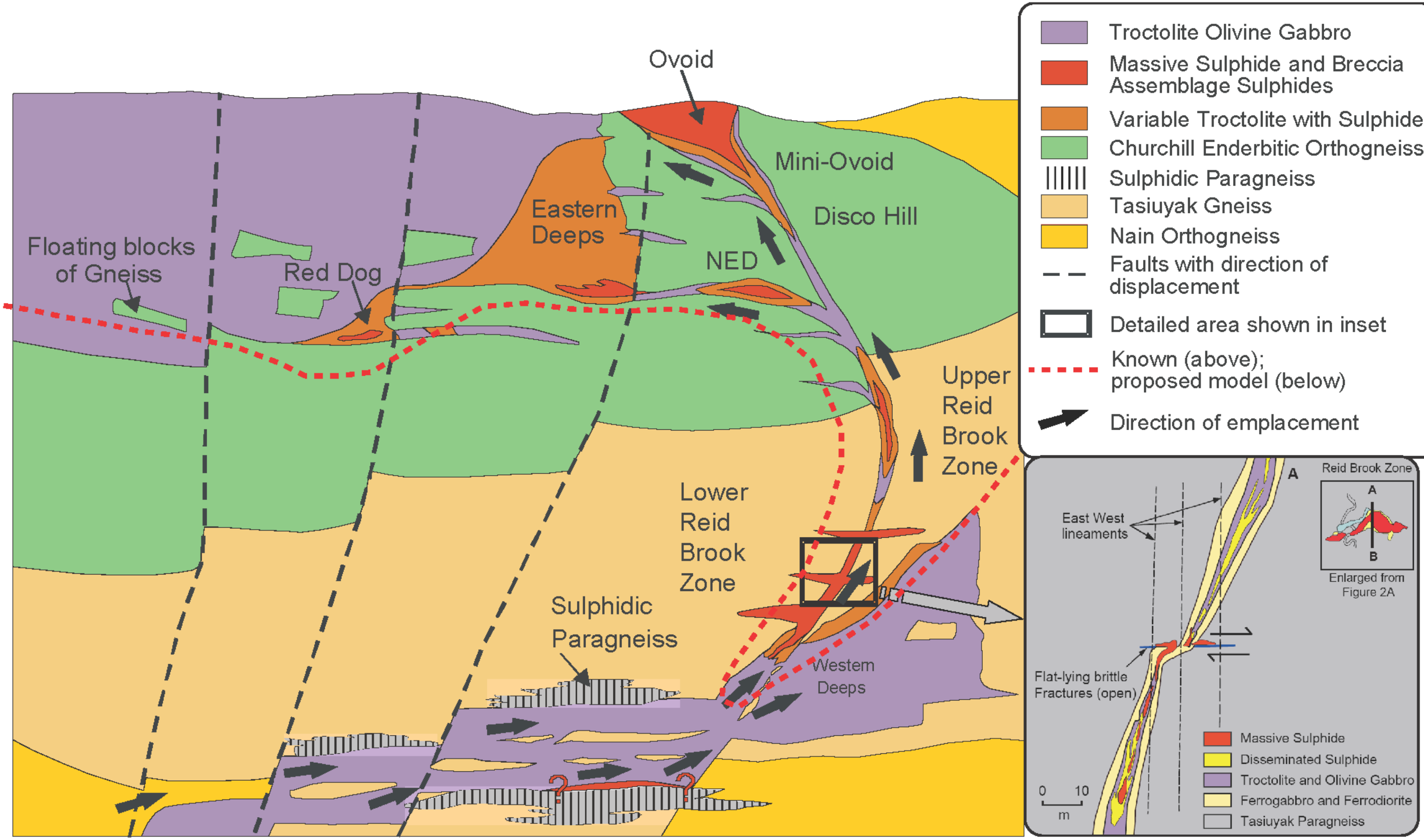
Sequential Emplacement of Sulfide-bearing silicate melts



Tang Zongli (1993)

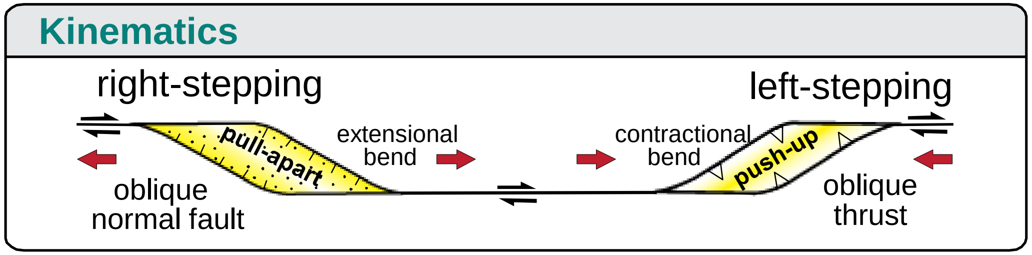
A Model for Voisey's Bay

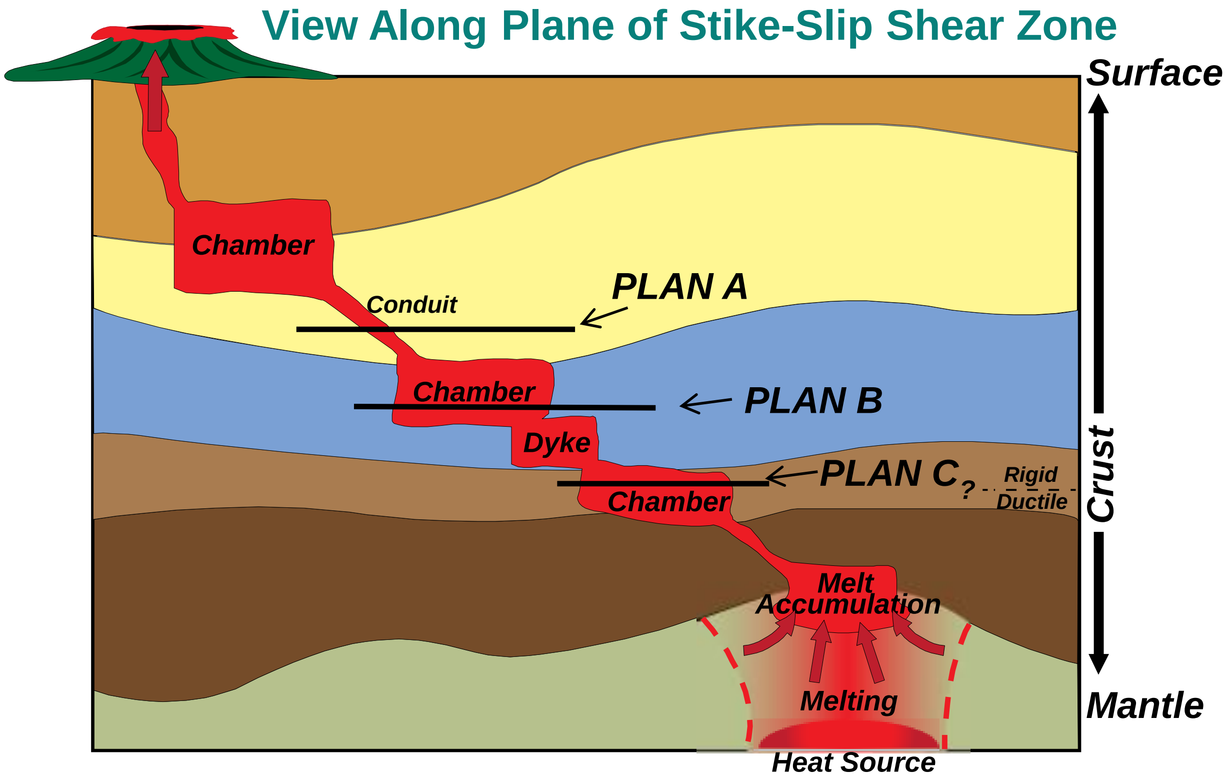
Compressed into a single N-S section

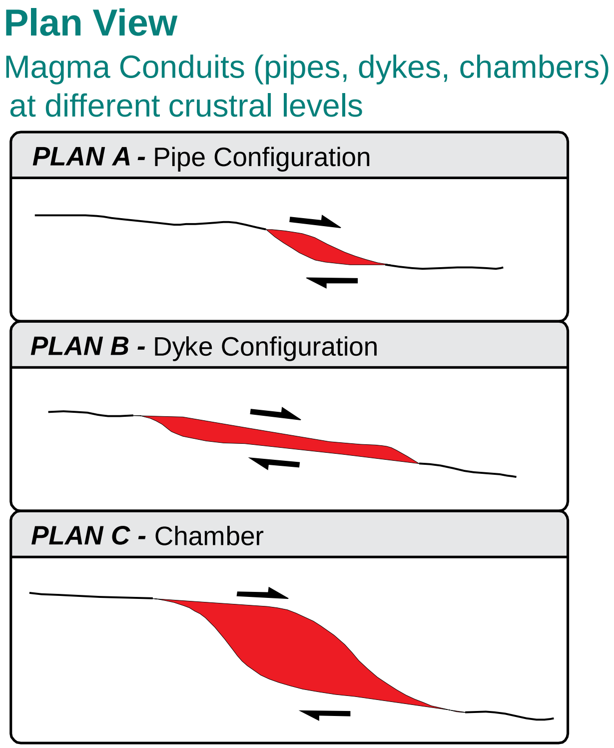


Lightfoot et al (2011)

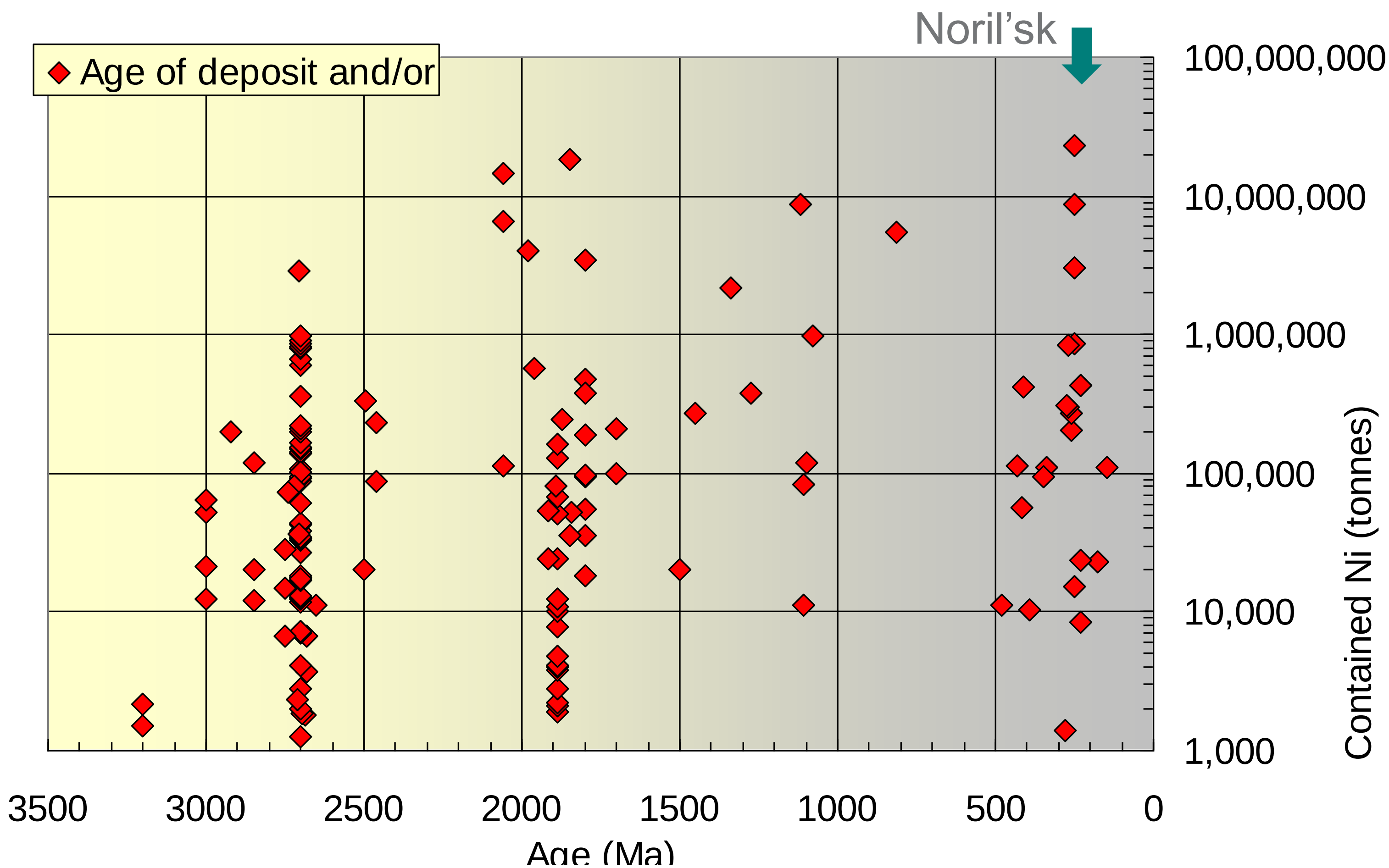
“China Model”: extensional spaces in transform fault systems act as “magma highways” from mantle to surface and control many small differentiated intrusions with nickel sulphide deposits

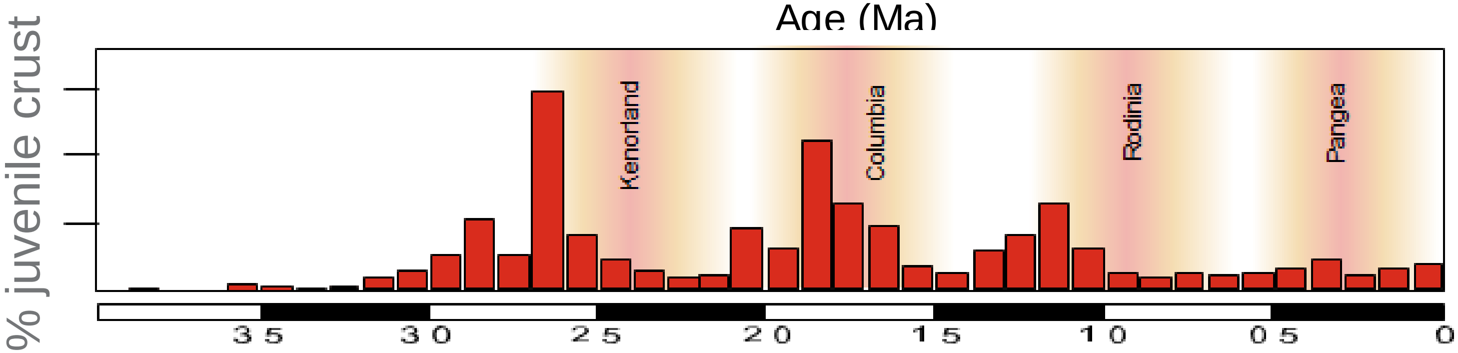






Nickel mineralization related to episodes of crustal growth





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