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Geology and geochemistry of mafic and ultramafic bodies in the Shebandowan mine area, Wawa-Abitibi terrane: implications for Ni-Cu-(PGE) and Cr-(PGE) mineralization, Ontario and Quebec

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Abstract

The Shebandowan Ni-Cu-(PGE) deposit occurs in the Shebandowan greenstone belt in the Wawa-Abitibi terrane. This deposit is one of a few economic Ni-Cu-(PGE) deposits in the Superior Province and one of a very few deposits worldwide that contains both Ni-Cu-(PGE) and Cr-(PGE) mineralization. The mafic-ultramafic successions in the area comprise abundant flows and sills of tholeiitic basalt and lesser Al-undepleted komatiite (MgO >18 wt%, Al_2O_3/TiO_2 = 15–25), the latter indicating separation from mantle sources at shallow levels. Siliceous high-Mg basalts (MgO 8–12 wt%, SiO_2 > 53 wt%, TiO_2 < 1.2 wt%, $La/Sm_{[MN]}$ < 1-2) are relatively abundant in the area and likely represent crustally contaminated komatiites. Ultramafic bodies in the Shebandowan mine area comprise at least three or four komatiitic sills (A-B, C, D) and at least two komatiitic flows (E, F), all of which are altered to serpentinites or talc-carbonate schists with relict igneous chromite and rare relict igneous orthopyroxene-clinopyroxene. Unit A-B contains pentlandite-pyrrhotite-chalcopyrite-pyrite-magnetite mineralization, occurring as massive sulfides, sulfide breccias, or stringers, and subeconomic chromite mineralization in contorted massive bands varying from a few millimetres up to 10 metres thick. The localization of massive and semi-massive Ni-Cu-(PGE) ores along the margins of Unit A and the paucity of disseminated and net-textured ores suggest tectonic mobilization. Chromite is typically zoned with Cr-Mg-Al-rich (chromite) cores and Fe-rich (ferrichromite/magnetite) rims due to alteration and/or metamorphism, but rarely contains amoeboid magnetite cores. The thickness of chromite in Unit B is too great to have crystallized in cotectic proportion from the komatiitic magma and a model involving dynamic upgrading of magnetite xenoliths derived from interflow oxide facies iron formations is being tested.

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Introduction

- Archean and Proterozoic magmatic Ni-Cu-(PGE) and Cr-(PGE) deposits preferentially hosted by komatiitic ultramafic rocks

- Close association between Ni-Cu-PGE and Cr is much less common, e.g. Bird River Sill, Manitoba; Esker Intrusive Complex, Ontario; *Shebandowan*, Ontario; and Uitkomst Complex, South Africa

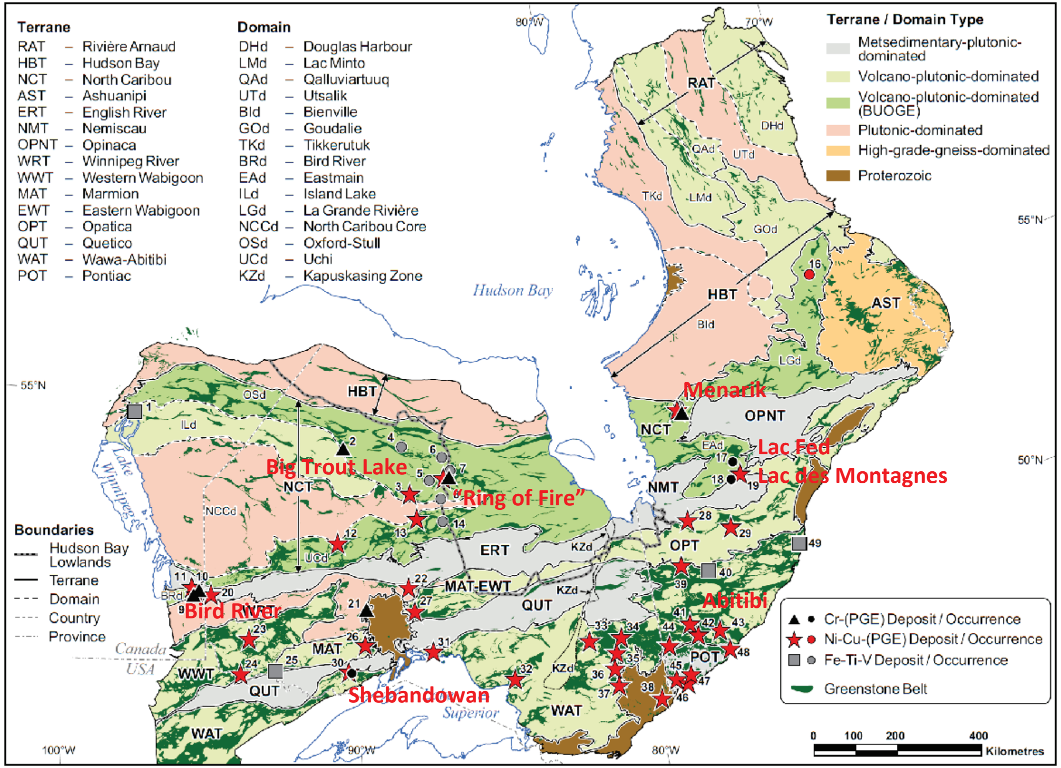
- Reasons for associated Ni-Cu-PGE and Cr mineralization are not clear, but must reflect a confluence of favourable factors

1) Intermediate-Mg, high-Cr komatiitic magma
2) High magma flux to facilitate thermomechanical erosion and high magma:sulfide and magma:oxide ratios (R factors)
3) Access to crustal sulfides *and* oxides

Regional Setting

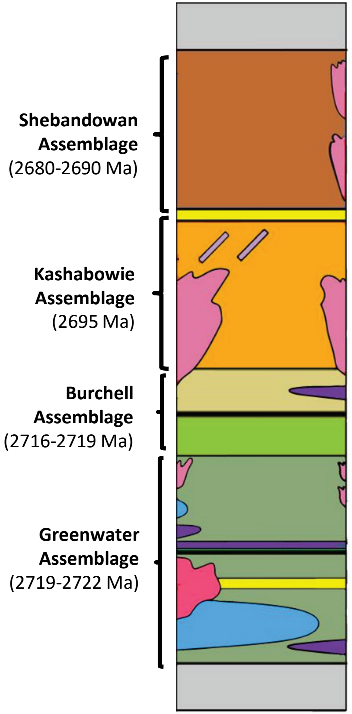
- **Abitibi-Wawa terrane** (ON-QC): numerous small-medium high-grade (e.g., Alexo, Shebandowan) and few large low-grade (e.g., Dumont) Ni-Cu-(PGE) deposits, but **Cr-(PGE) mineralization restricted to Shebandowan**

- **Bird River – Uchi – Oxford-Stull – La Grande – Eastmain “BUOGE superdomain”** (ON-QC): few known **world-class Cr-(PGE) deposits** (e.g., Black Thor-Blackbird), numerous small **Cr-(PGE) deposits/prospects** (Bird River, Lac des Montagnes, Menarik), and several economic **Ni-Cu-(PGE) deposits** (e.g., Makwa-Mayville, Thierry, Eagle’s Nest, Nisk)

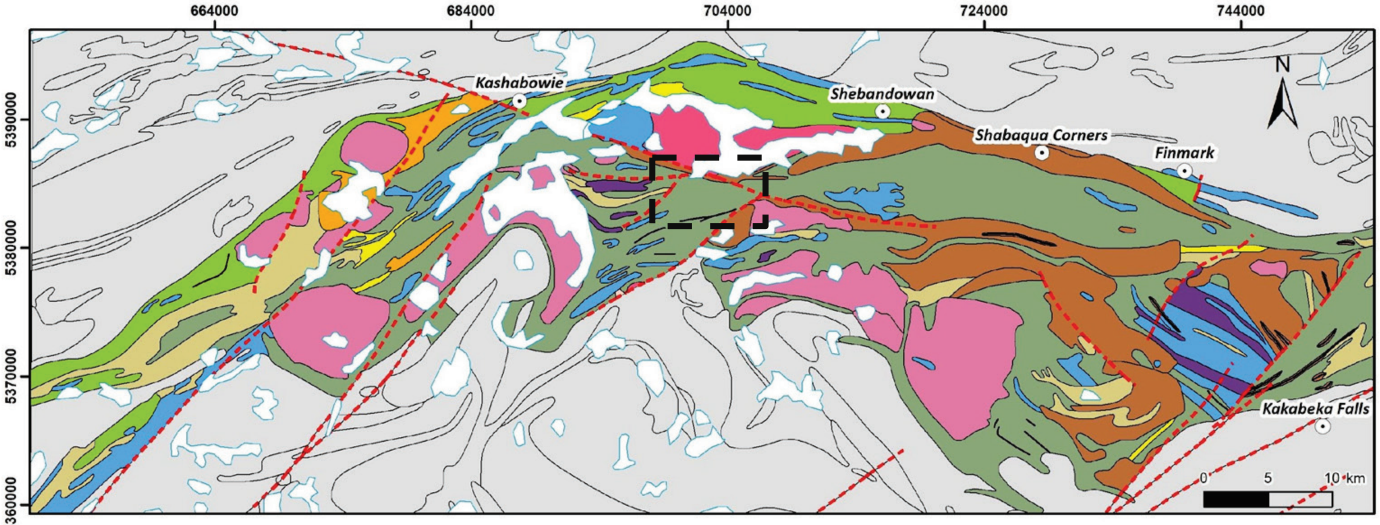


Houlé et al. (2020) *TGI5-OF*

Shebandowan Greenstone Belt



Modified from Sotiriou et al. (2019) *Lithos*



Modified from Lodge (2016) *Prec. Res.*

Legend:

- 🟫 *Metasedimentary rocks with minor calc-alkaline to alkaline intermediate volcanic rocks and intrusions*
- 🟧 *Intermediate volcanic and intrusive rocks*
- 🟨 *Intermediate to felsic volcanic rocks*
- 🟩 *Calc-alkaline basalts*
- 🟨 *Felsic volcanic rocks*
- 🟩 *Massive to pillowed tholeiitic basalts*
- 🟥 *Tonalites, granodiorites, granites, monzonites and syenites intrusions*
- ⬛ *Banded iron formation*
- 🟪 *Ultramafic flows and sills*
- 🟦 *Gabbro intrusions*

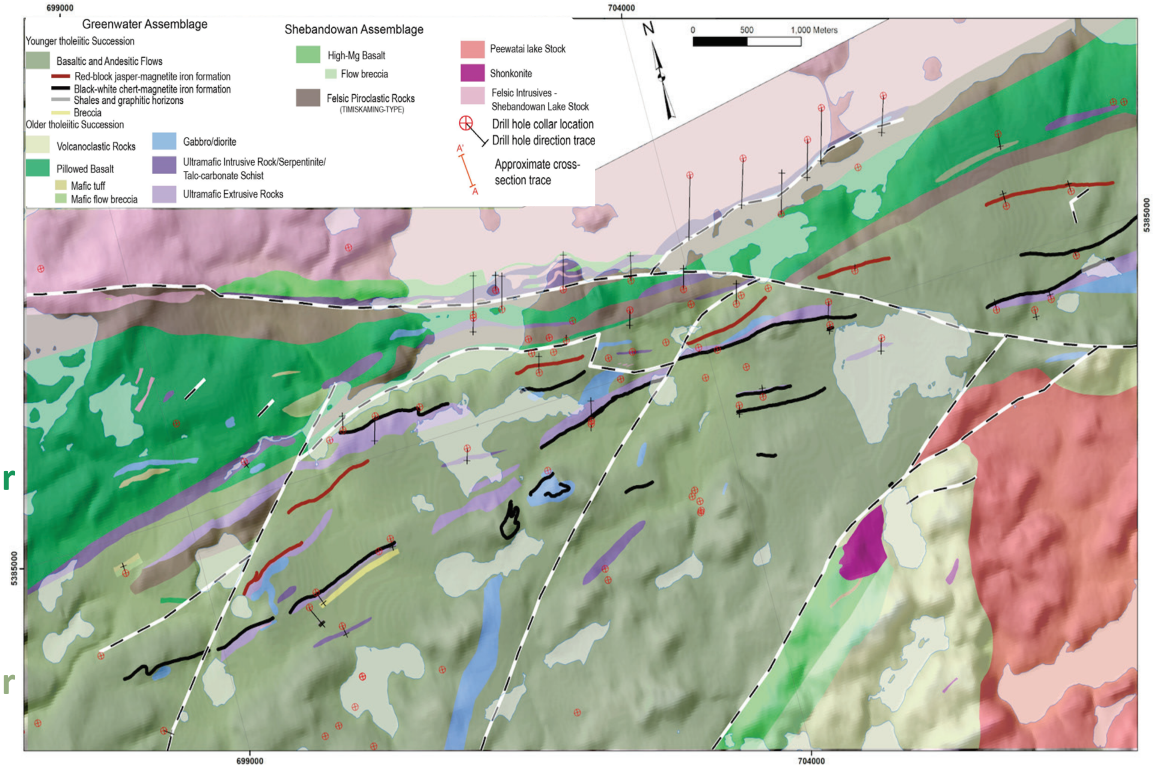
Shebandowan Ni-Cu mine - Geology

Greenwater Assemblage

- **Older succession**
  - Tholeiitic basaltic flows, flow breccias, and tuffs
  - Haines Gabbro
  - Ultramafic sills
- **Younger succession**
  - Tholeiitic to calc-alkaline basalts
  - Ultramafic flows
  - Interflow oxide-chert iron formation

Shebandowan Assemblage

- High-Magnesian basalts
- Timiskaming-type rocks
- Granitoid intrusions



Older

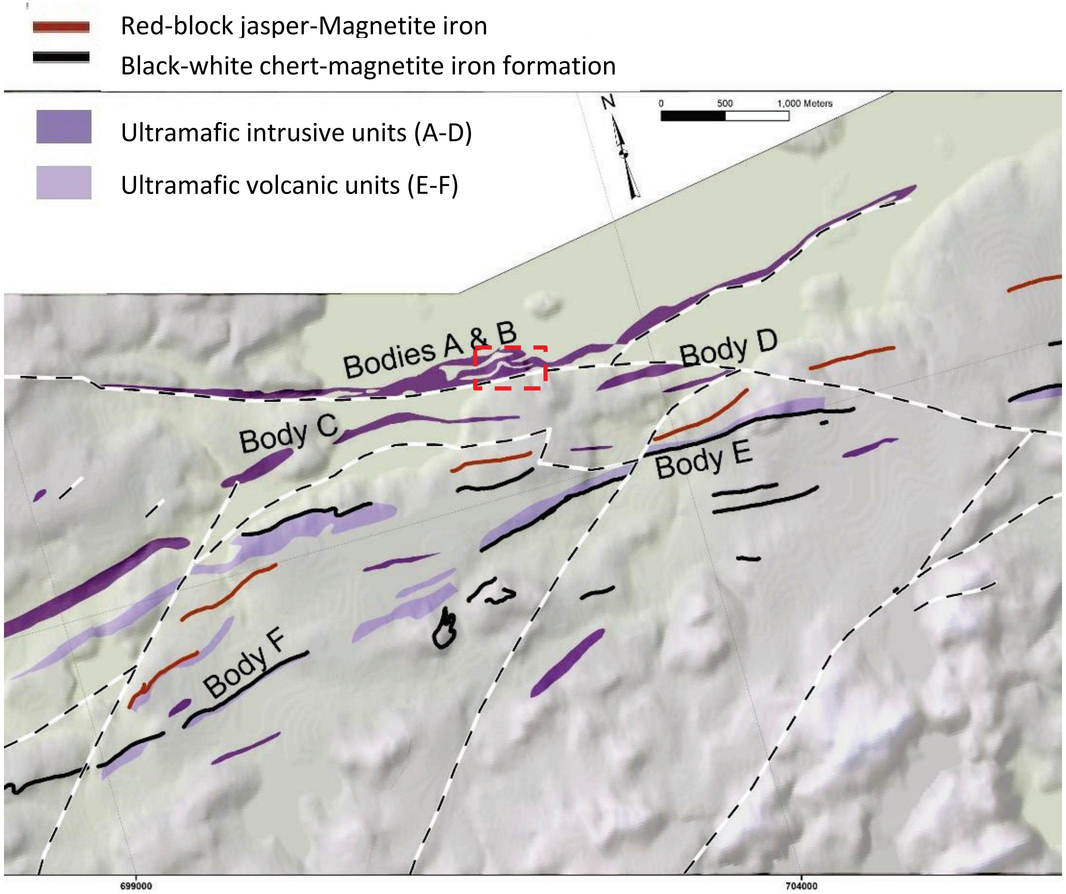
Younger

Modified from Morton (1982) *Ph.D.*

Ultramafic bodies

- **3 to 4 “sills”** (A-B, C, D)
  2 “flows” (E, F)

- **Thinner sills/flows** (C-D-F) are **undifferentiated** peridotite
- **Thicker sills/flows** (A-B-E) are **differentiated** harzburgite to olivine gabbro
- Flows are **associated with oxide-chert iron formation** and **basaltic hyaloclastite** (to be confirmed)
- Variably altered to **greenschist facies** serpentine – magnetite ± tremolite ± talc ± carbonate assemblages



Modified from Morton (1982*) Ph.D.*

Structural complexity

Deformation stages

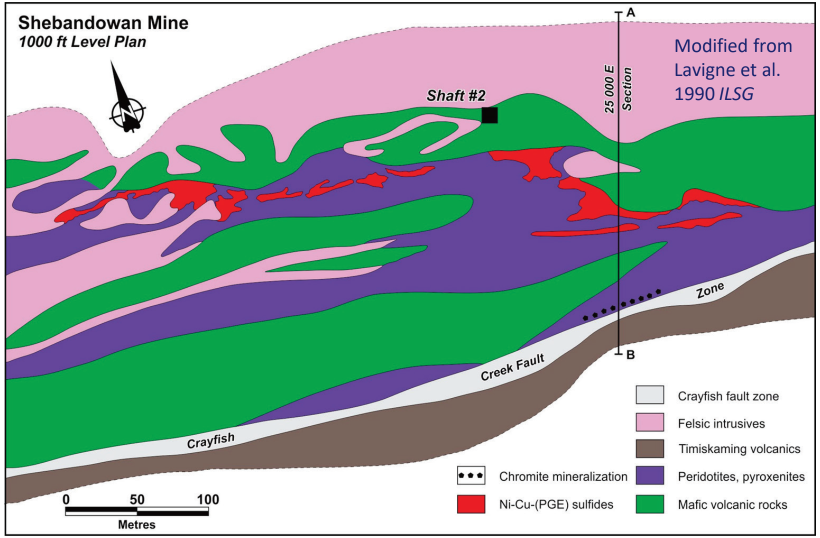
D1: WSW-plunging mineral lineations

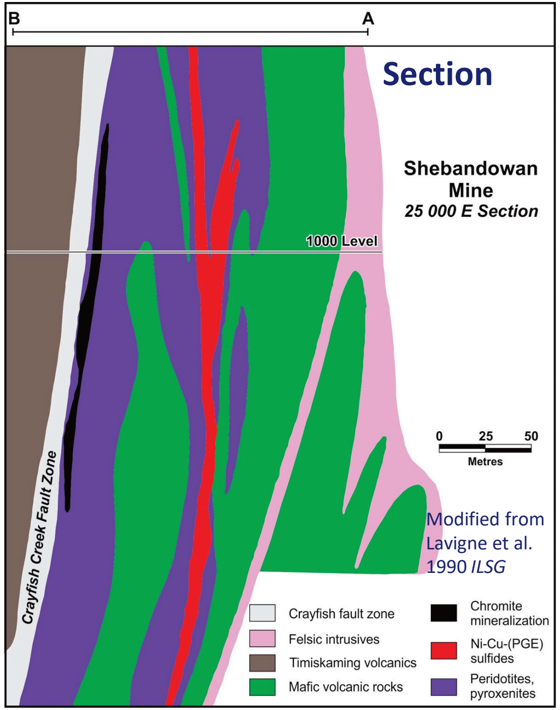
D2: ENE-plunging isoclinal folds and mineral lineations, steeply dipping foliations

D3: N-S steeply plunging kink folds

D4: Strike-slip faulting (Crayfish Creek Fault)

Plan



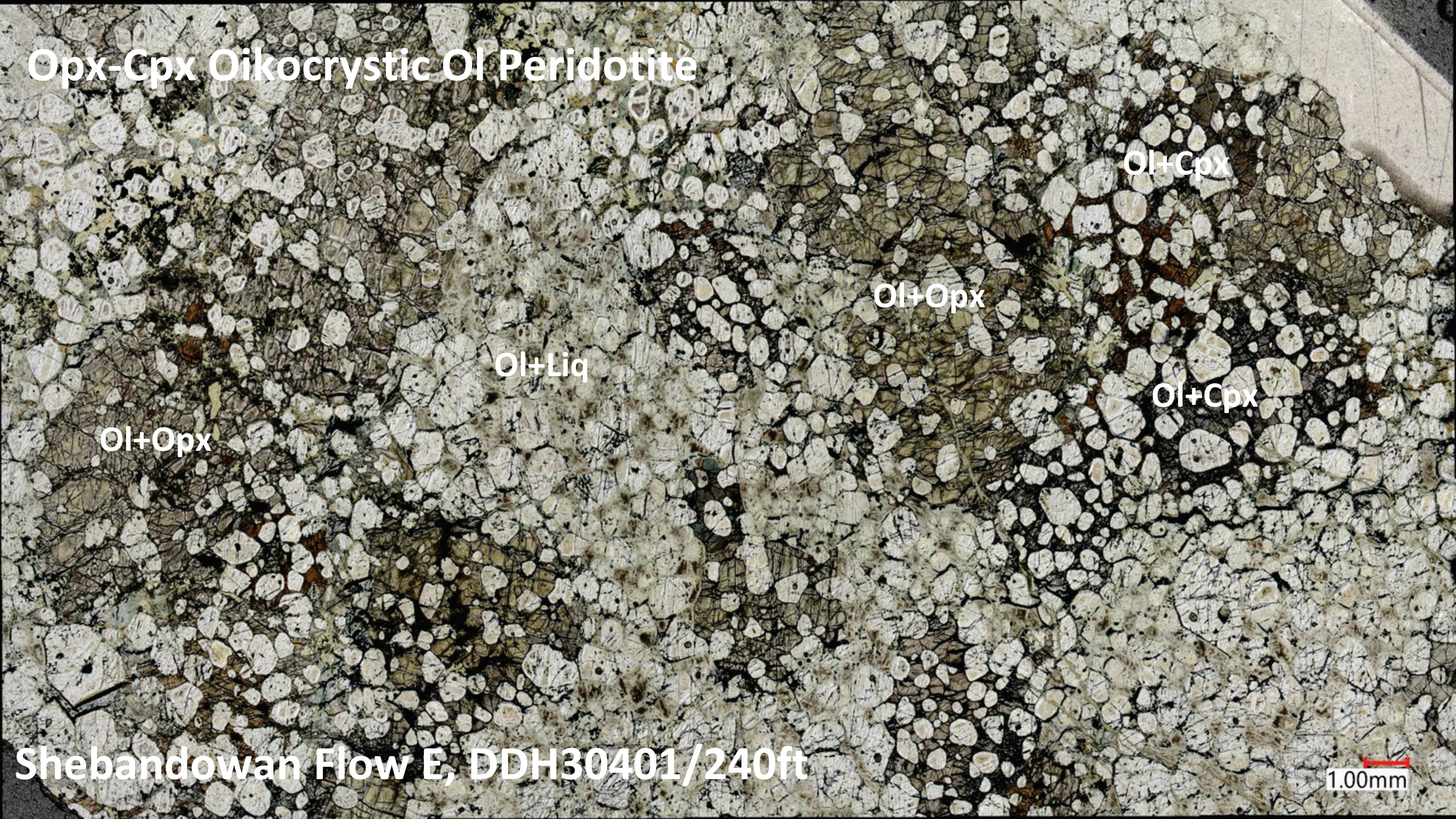


Controversial facing direction

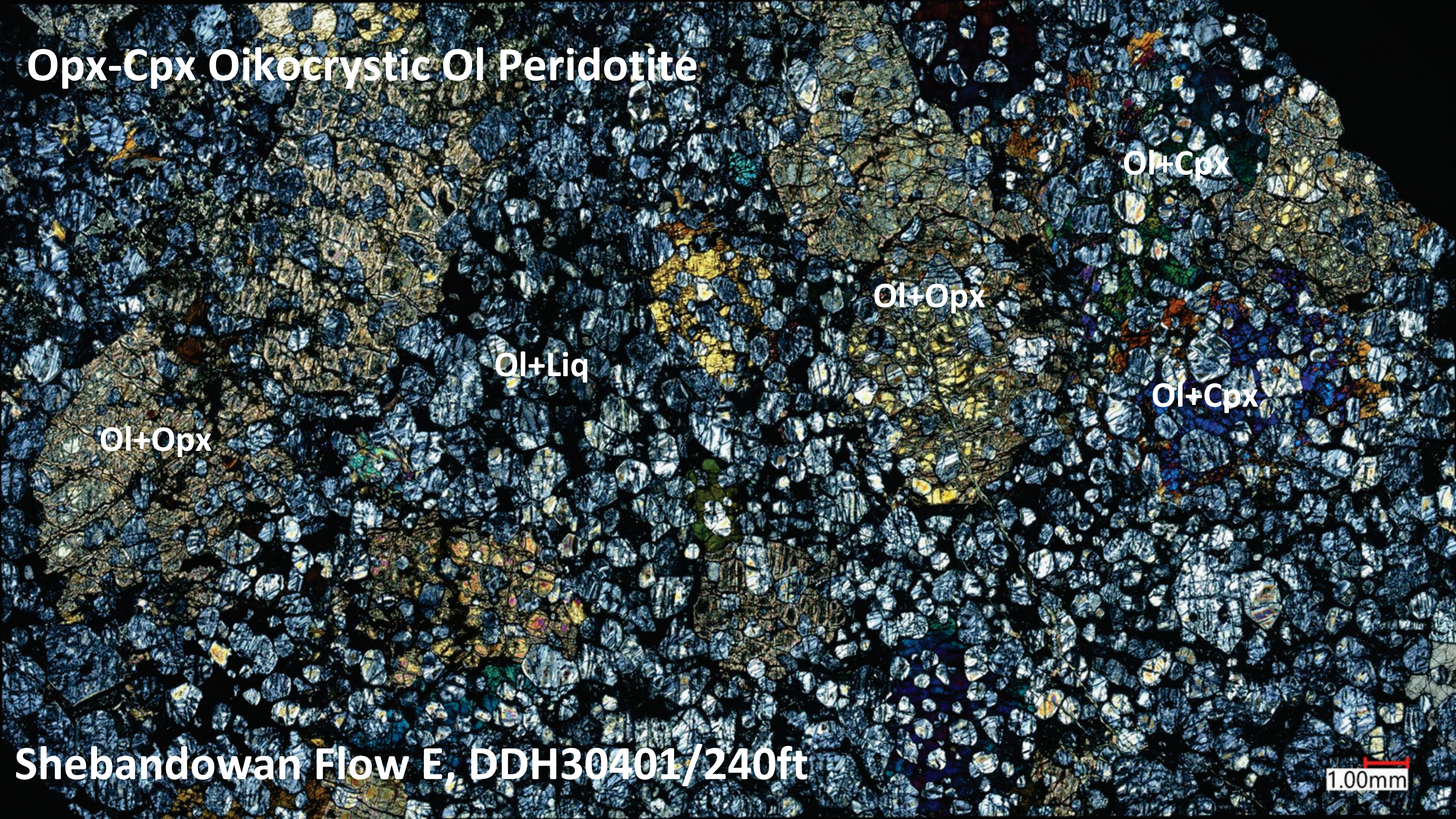
From plan view facing South, sulfides near bottom, chromite on top (Osmani, 1997 - *OGS Report*)

From structural and stratigraphic considerations south of the fault, sulfide ore lies on top of ultramafic sill (Morton 1992 - *Ph.D.*)

Ore may be mobilized post-folding - planar sheet sheared along contacts in a system with isoclinal folding


Opx-Cpx Oikocrystic Ol Peridotite
Ol+Cpx
Ol+Opx
Ol+Liq
Ol+Cpx
Ol+Opx
Shebandowan Flow E, DDH30401/240ft
1.00mm

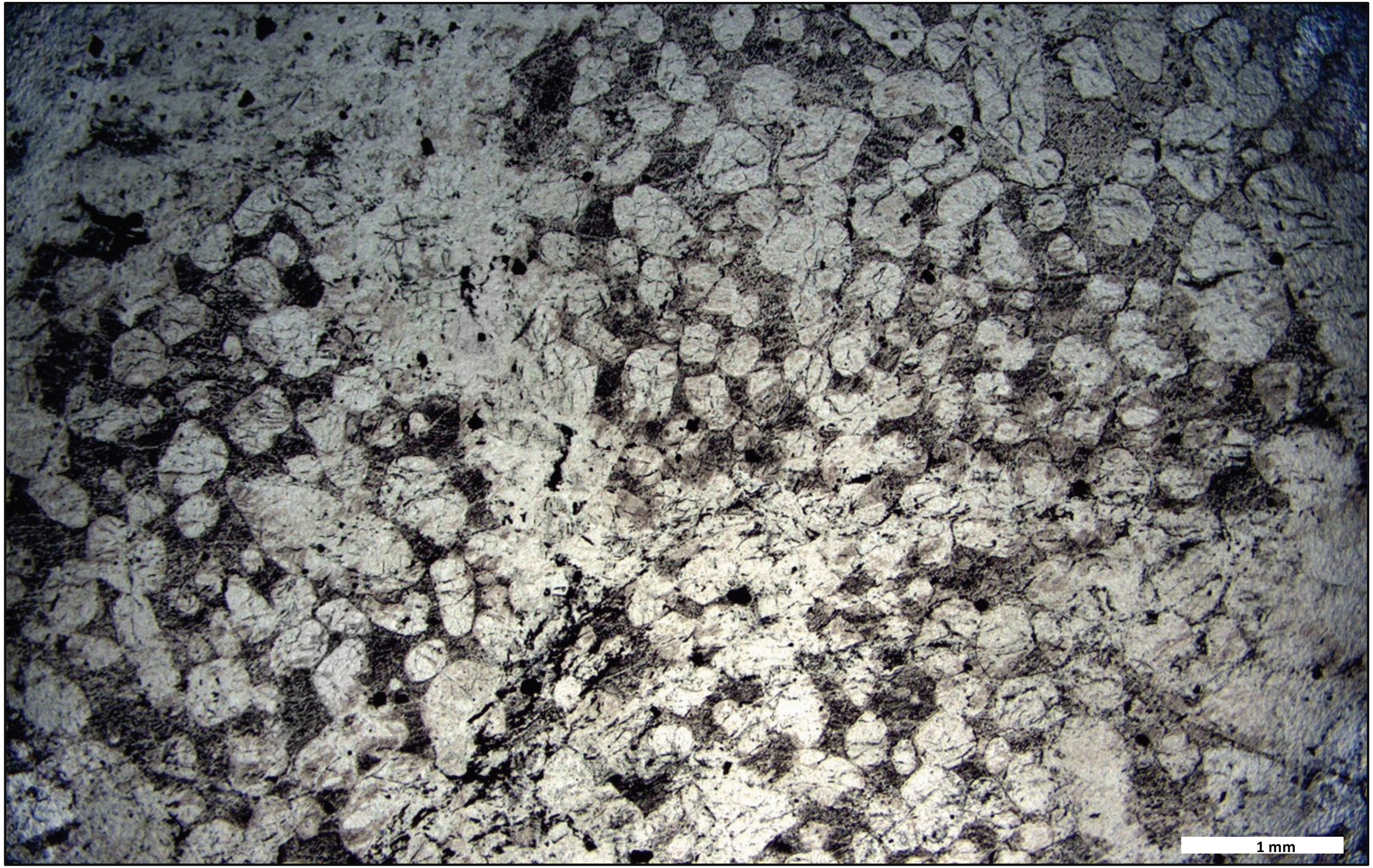
Opx-Cpx Oikocrystic Ol Peridotite



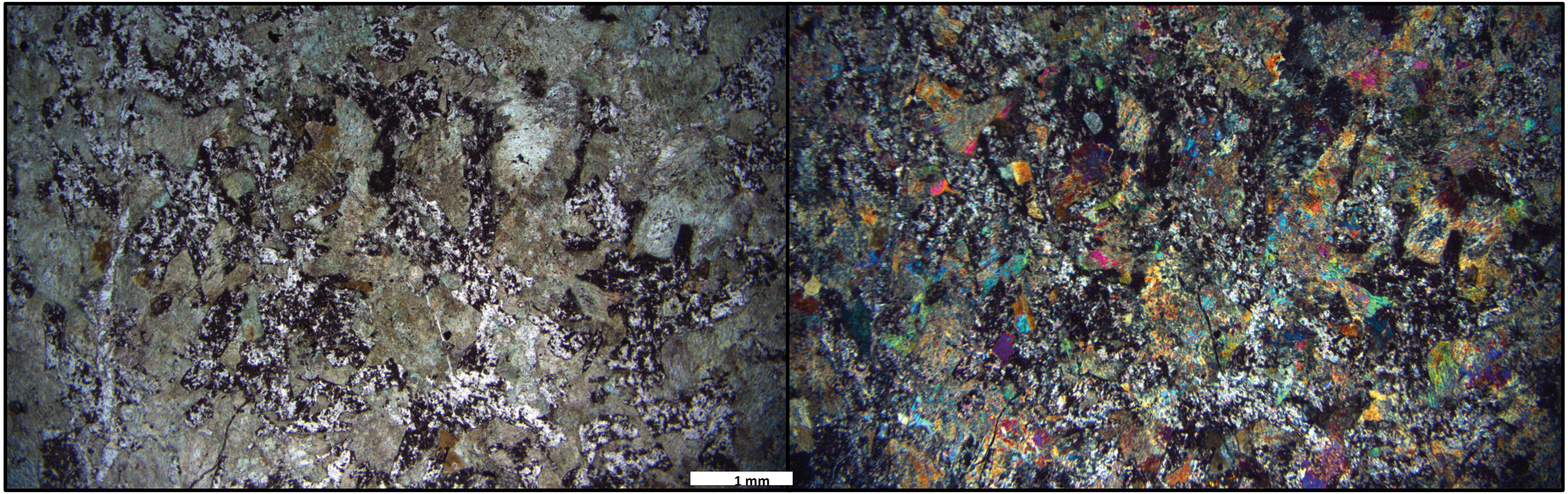
Shebandowan Flow E, DDH30401/240ft

Sill B

Harzburgite;
Olivine (Ol) +
Orthopyroxene (Opx) +
disseminated chromite,
altered to serpentine +
talc + dolomite +
magnetite
DDH 30468-1030 ft –
Plane polarized light

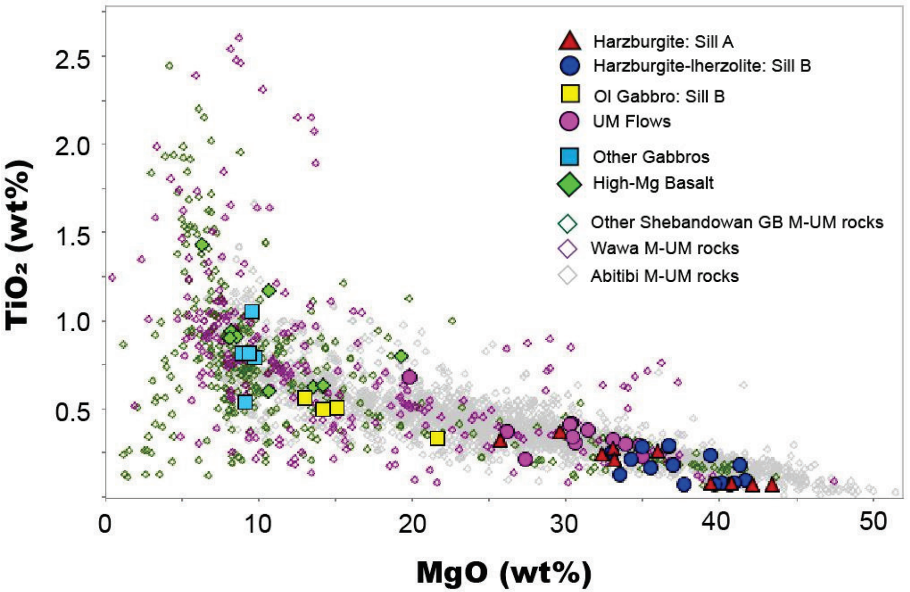


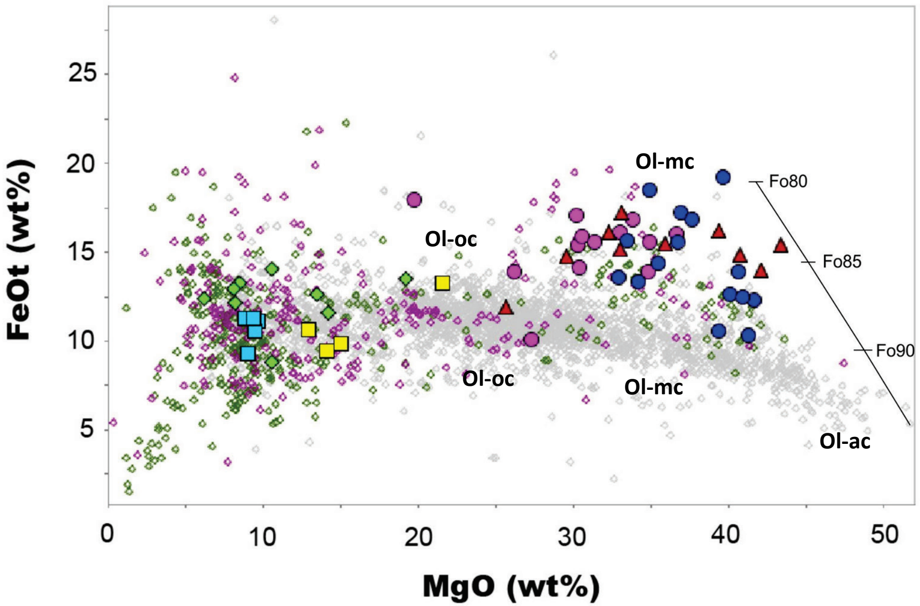
Sill B – Upper zone



Gabbro: Olivine, clinopyroxene, and plagioclase altered to serpentine, tremolite-actinolite + talc (sample R20 – Ramp section)

Shebandowan Lithogeochemistry





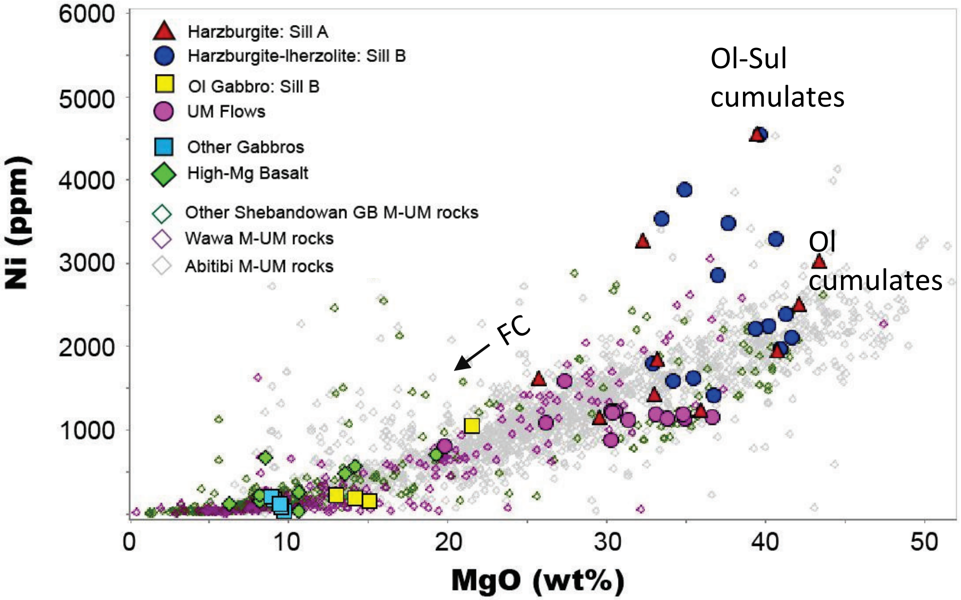
- Well-defined olivine accumulation-fractionation trend
- Sill A-B varies between 44 and 13 wt% MgO

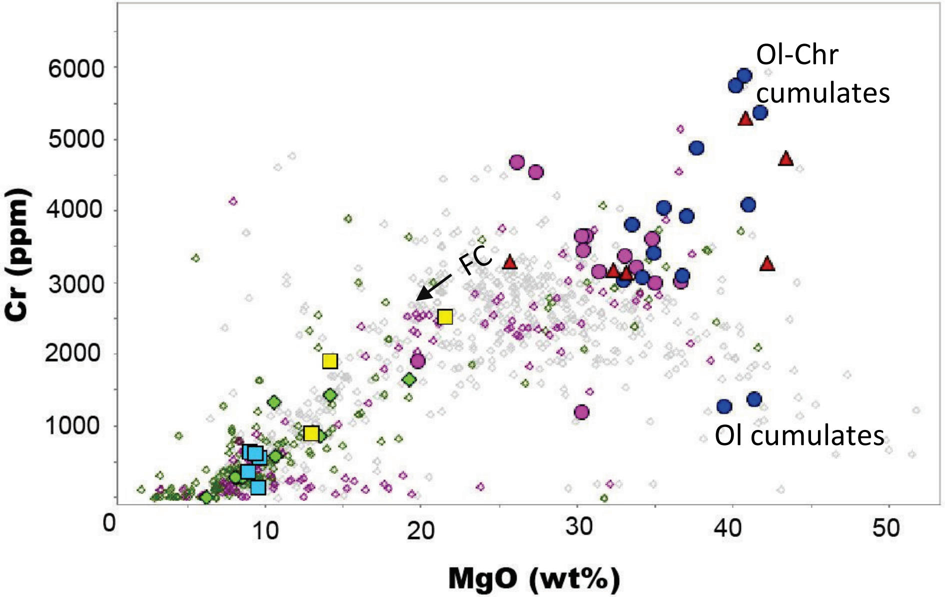
- **Higher Fe** contents of Shebandowan cumulate rocks indicate that they contain **lower-Fo olivine** and are derived from **lower-Mg magmas** than the majority of Abitibi komatiites

UM = ultramafic, M-UM = mafic-ultramafic, GB = gabbro

Ol = olivine, oc = orthocumulate, mc = mesocumulate, ac = adcumulate

Shebandowan Lithogeochemistry





- Olivine fractionation/accumulation trend
- Higher Ni samples contain sulfides

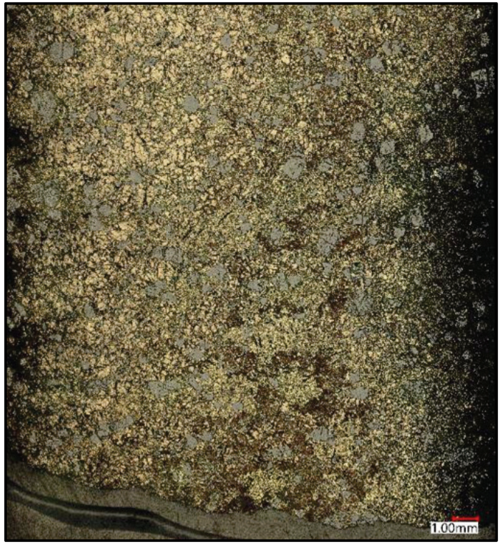
Ol = olivine, Sul = sulfides, Chr = chromite, UM = ultramafic, M-UM = mafic-ultramafic, GB = gabbro, FC = fractional crystallization

- Dominantly Olivine-(Chromite) fractionation/accumulation trend
- Mostly Cr-saturated, but some in Sill B are Olivine-only cumulates
- Indicates that magma evolved from Chromite-undersaturated to Chromite-saturated

Mineralization – Ni-Cu-(PGE)

Massive sulfides

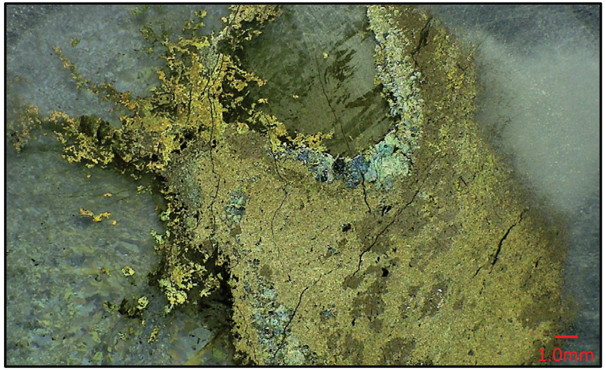
DDH 45171-50 ft Sill A



DDH 78826/145

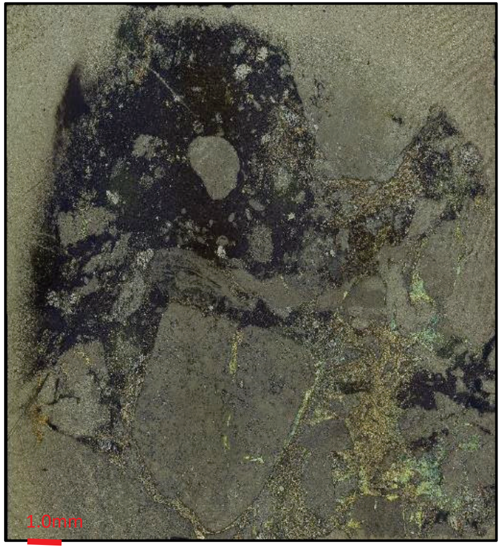
Average composition *(pXRF, n = 7)*
8.4% Ni, 2.0% Cu, 0.2% Co
(Houlé et al., unpublished data)

- Pyrrhotite-Pyrite-Chalcopyrite-Pentlandite, predominantly massive and semi-massive breccias with negligible disseminated or net-textured sulfides
- 10.2 Mt @ 1.9% Ni, 1.0% Cu, and 3 g/t Au+Pt+Pd
- Lower Ni/Cu ratio than expected

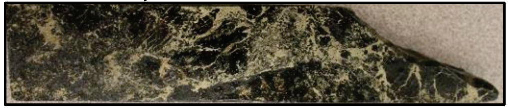


Breccia sulfides

Sample I-15a Sill A



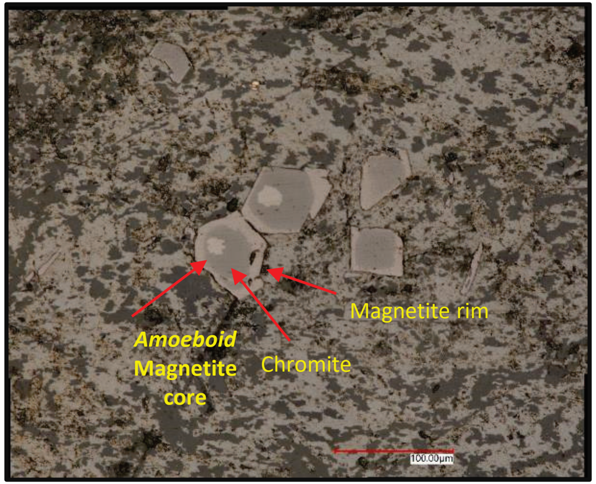
DDH 78826/134.5



Average composition *(pXRF, n = 6)*
3.7% Ni, 1.8% Cu, 0.2% Co
(Houlé et al., unpublished data)

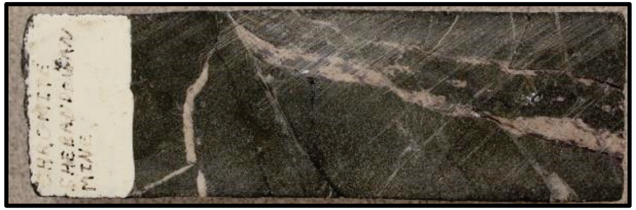
Mineralization – Chromite

Most rocks contain **cotectic abundances** (50-100:1) of Ol and Chr



Typically altered with **Cr-Mg-Al-rich cores** (chromite) and **Fe-rich rims** (ferrichromite/magnetite) Rare amoeboid magnetite cores (DDH 30414-240ft Sill C)

Sill B contains an up to **10m-thick** layer of massive **chromitite**



Massive Chromitite

DDH 78819/587

Average composition ***(pXRF, n = 6)***

26.5% Cr, 0.3% Ti, 0.4% Ni

(Houlé et al., unpublished data)

Layered Chromitite

Intercalation of massive chromitite and peridotite

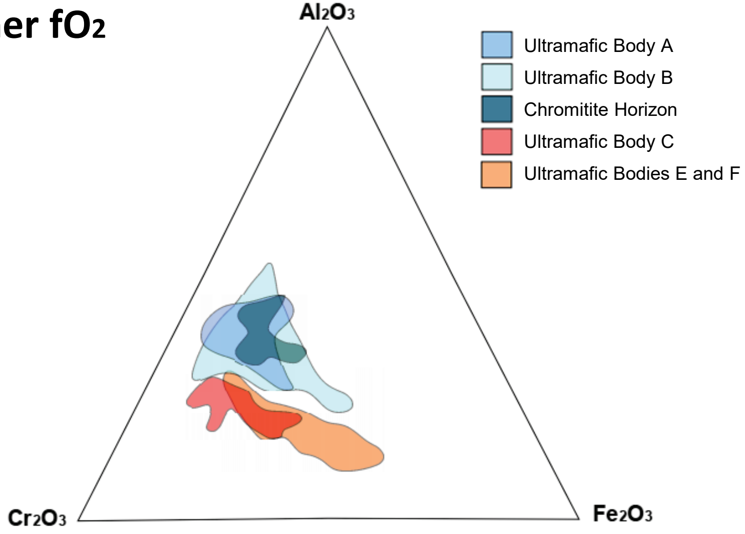
(Photos by M. Houlé)

Chromite Chemistry

Sills: higher Al, lower Ti-Fe
Flows: lower Al, higher Ti-Fe

Higher-Al, lower Ti-Fe chromite formed at, **lower fO_2**

Lower-Al, higher Ti-Fe chromite formed at, **higher fO_2**



UM Body	TiO_2 (wt%)	MnO (wt%)	Fe^{3+} / (Fe^{3+} +Cr^{3+} +Al^{3+})
Sill A peridotite	0.5	1.1	0.182
Sill B peridotite	0.8	1.3	0.183
Sill B chromitite	0.6	0.4	0.165
Sill C peridotite	1.9	1.1	0.185
Flow E peridotite	4.0	1.7	0.332
Flow F peridotite	3.9	1.7	0.349

From Morton 1982 *Ph.D.*

	Sill A	**Sill B**	**Sill C**	**Sill D**	**Flow E**	**Flow F**
Stratigraphic Position	Older basaltic succession		Older basaltic succession	Older basaltic succession	Younger basaltic succession	Younger basaltic succession
Thickness/Length	20-150m* x 6 km		37m x 1.25 km	80m x 0.8 km	115m x 3 km	18m x 1 km
Lithologies	harzburgite – Olivine gabbro		harzburgite – lherzolite	harzburgite – lherzolite	harzburgite – Olivine gabbro	harzburgite – lherzolite
Differentiation	strong		weak	weak	strong	weak
Ol Enrichment	moderate		high	high	moderate	high
Chr TiO_2 (%)	ave. 0.5		ave. 1.9 (bimodal)	no data	ave. 4	
Chr MnO (%)	ave. 1.1		ave. 1.1	no data	ave. 1.7	
Chr Al_2O_3 (%)	high		intermediate	no data	ave. 8	
Chr $Fe^{3+}/Fe^{3+}+Al^{3+}+Cr^{3+}$	no data		no data	no data	ave. 0.34	
Log fO_2 (ΔFMQ)	**-2 to 0**	0-2	ave. 2	no data	0-2**	2-4**
Whole rock Mg#	**0.83** - 0.78	**0.86** - 0.69	no data	no data	ave. 0.66	0.80 to 0.76
Whole rock CaO/TiO_2	**ave. 19**	**ave. 14**	no data	no data	no data	ave. 8
Whole rock Al_2O_3/TiO_2	**ave. 21**	**ave. 21**	no data	no data	no data	ave. 12
Ni-Cu-(PGE) mineralization	**economic**	none	none	none	none	none
Chromite mineralization	none	**subeconomic**	none	none	none	none

Data from Morton 1982 *Ph.D.* *multiphase, ** high Ti may underestimate fO2 Mg# = Mg/ (Mg+Fe) ave. = average value

Implications for Cr and Ni-Cu-(PGE) mineralization

Host Units

- Moderately high MgO contents, presence of abundant Olivine with Orthopyroxene-Clinopyroxene rather than just Olivine-Clinopyroxene suggest crystallization from **contaminated low-Mg komatiitic magma**
- Excess cumulus Olivine-Orthopyroxene suggests **flow-through crystallization**
- Moderate-strong differentiation of thicker units suggest that they **ponded after accumulating Olivine-Orthopyroxene**

Ore Localization

- Massive and semi-massive sulfides along the margins of ultramafic bodies and rare disseminated and net-textured ores suggest **tectonic mobilization**
- Higher-than-expected Cu/Ni ratios suggest **incorporation of Cu-rich crustal sulfides** (Morton 1982 *Ph.D.*) or **selective mobilization of Cu-PPGE-rich ISS** relative to Ni-IPGE-rich MSS (to be tested)

PPGE = Pt-subgroup of platinum group elements (Pd, Pt, Rh), ISS = intermediate solid solution, MSS = monosulfide solid solution

Sulfur Sources

- Magmas can dissolve and exsolve **only very small amounts of sulfide**
- Most deposits of this type formed by **upgrading of sulfide xenomelts** (Lesher & Campbell 1993 *Econ. Geol.*)
- No known local S sources at Shebandowan mine, but there are **S-rich argillites elsewhere in the belt**

Black sulfidic argillite intercalated with ultramafic flows east of mine area
(Photo from Hinz 2018 M.Sc.)

Oxide Sources

- Magmas can dissolve and crystallize **only very small amounts of chromite**
- Thickness of chromitite at Shebandowan (also Bird River, Lac Fed, Lac des Montagnes, Menarik) are much less than Black Thor, but still **greater than can be produced through changes in solubility** (e.g., magma mixing, fractional crystallization/assimilation fractional crystallization, changes in pressure)
- Partial melting of iron formation and **upgrading of magnetite xenocrysts** (Lesher et al. 2019 *Geology*) is being tested (including nature of amoeboid magnetite cores)

Interflow black chert magnetite iron formation

Future work in the Shebandowan Mine

- Data compilation from companies
- Fieldwork including field mapping and core logging with sampling the key geological units at the mine site and at the Ontario Geological Survey core logging facility in Conmee Township near Thunder Bay
- Petrographic work
- Mineral chemistry on oxides and silicate minerals *(EPMA and LA-ICP-MS)*
- Whole-rock and ore geochemistry of the key geological units including both mineralization types – Ni-Cu-(PGE) and Cr-(PGE)
- Sulfur, Rhenium, Osmium and Nd isotope geochemistry

Acknowledgments

Canada

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