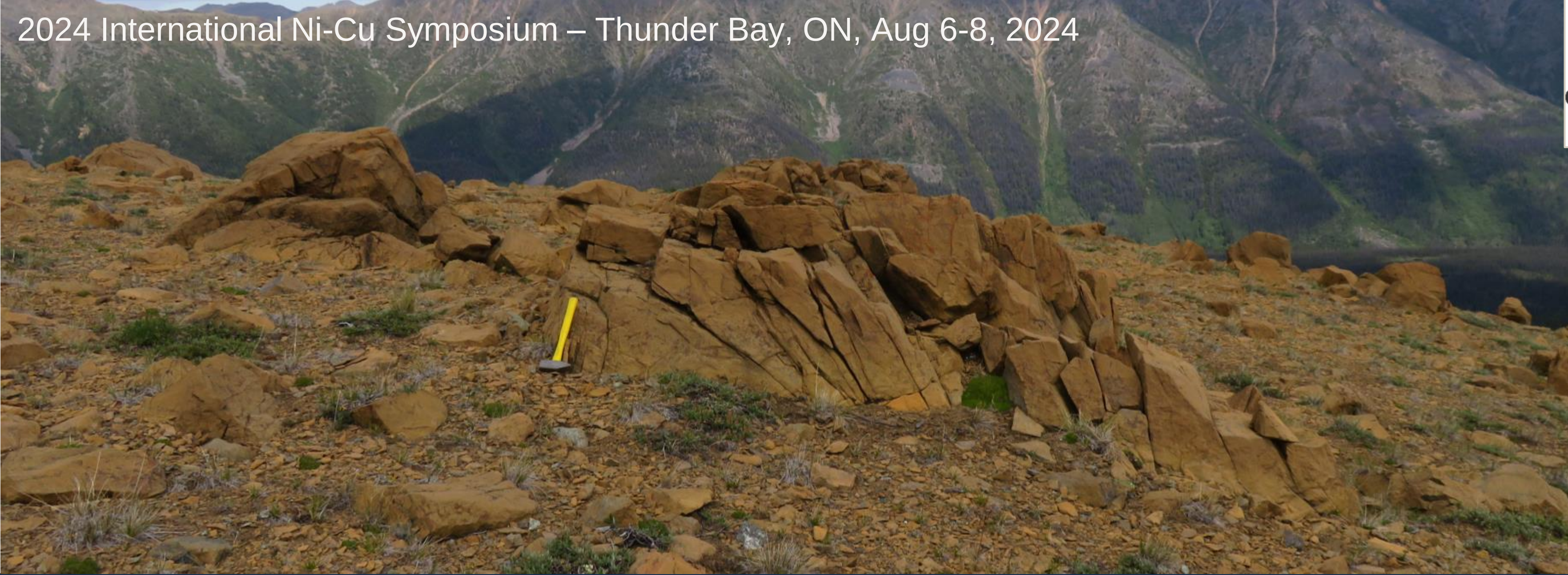
2024 International Ni-Cu Symposium – Thunder Bay, ON, Aug 6-8, 2024



Primitive arc magmatism and the development of magmatic Ni-Cu-PGE mineralization in Alaskan-type ultramafic-mafic intrusions

Milidragovic, D., Nixon G.T., Spence, D.W., Nott, J.A., Goan, I.R., Scoates, J.S.

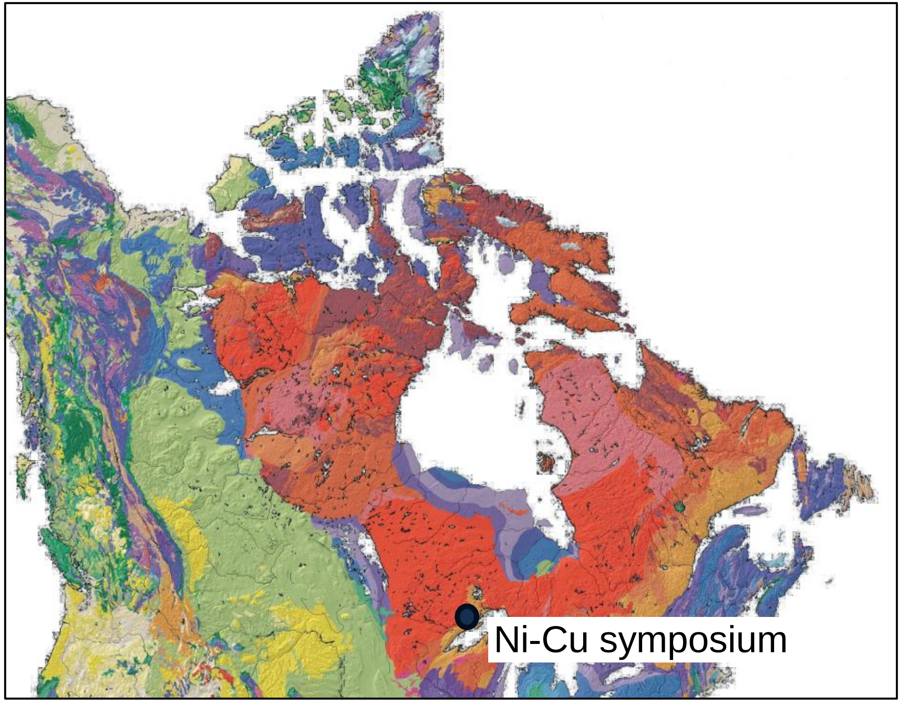
Natural Resources Canada | Ressources naturelles Canada

Canada

Message:

- Primitive arc magmas are inherently water-rich and oxidized and very different from intraplate and MOR magmas.

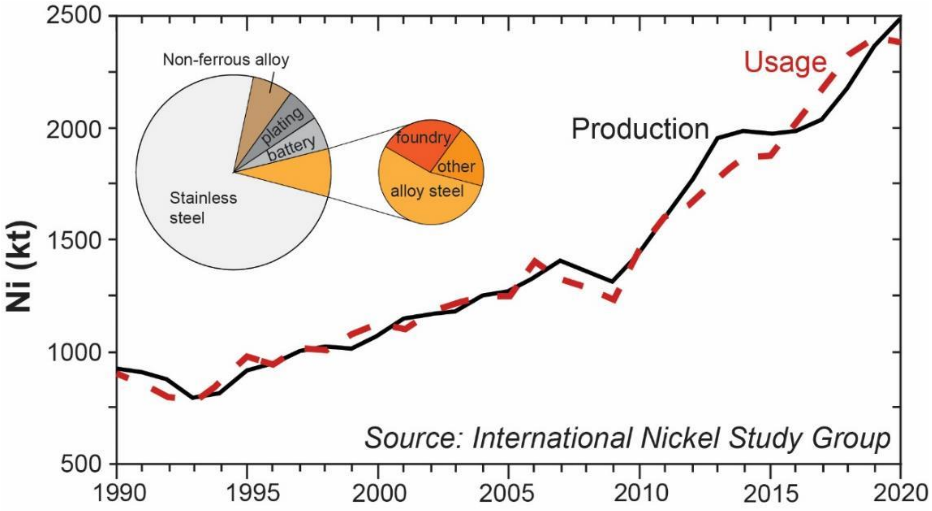
- Because of this, the styles of magmatic mineralization in arc-related ultramafic-mafic intrusive rocks are very different from those of conventional Ni-Cu deposits

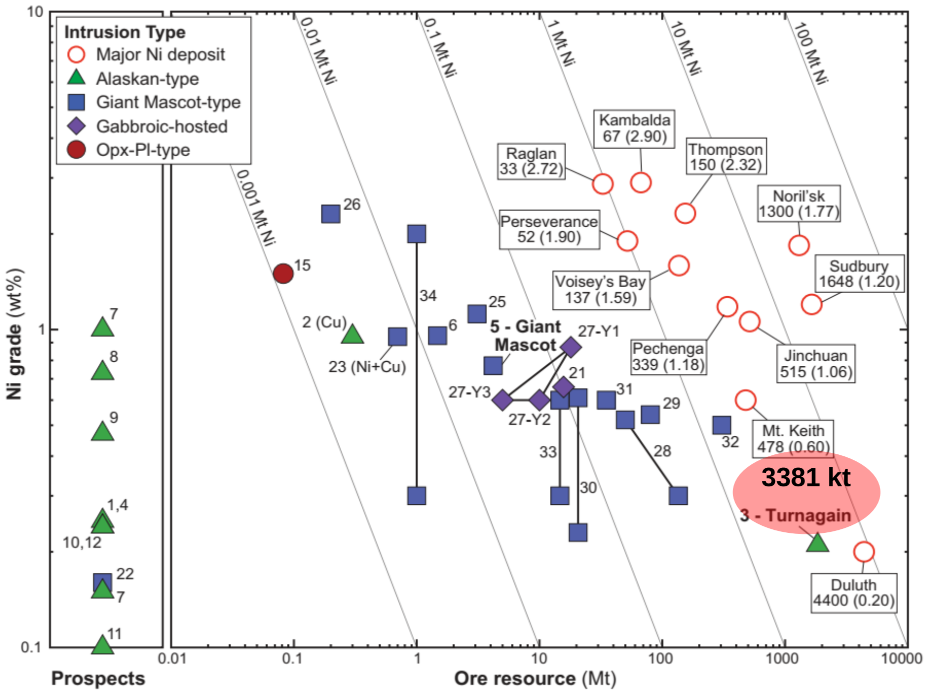


Outline

- Research rationale
- Primitive convergent margin (Alaskan-type) intrusions
- Mineralization
  - Crustal assimilation
  - Intrinsic magma properties

Research rationale:
need for new Ni (Cu-PGE) resources



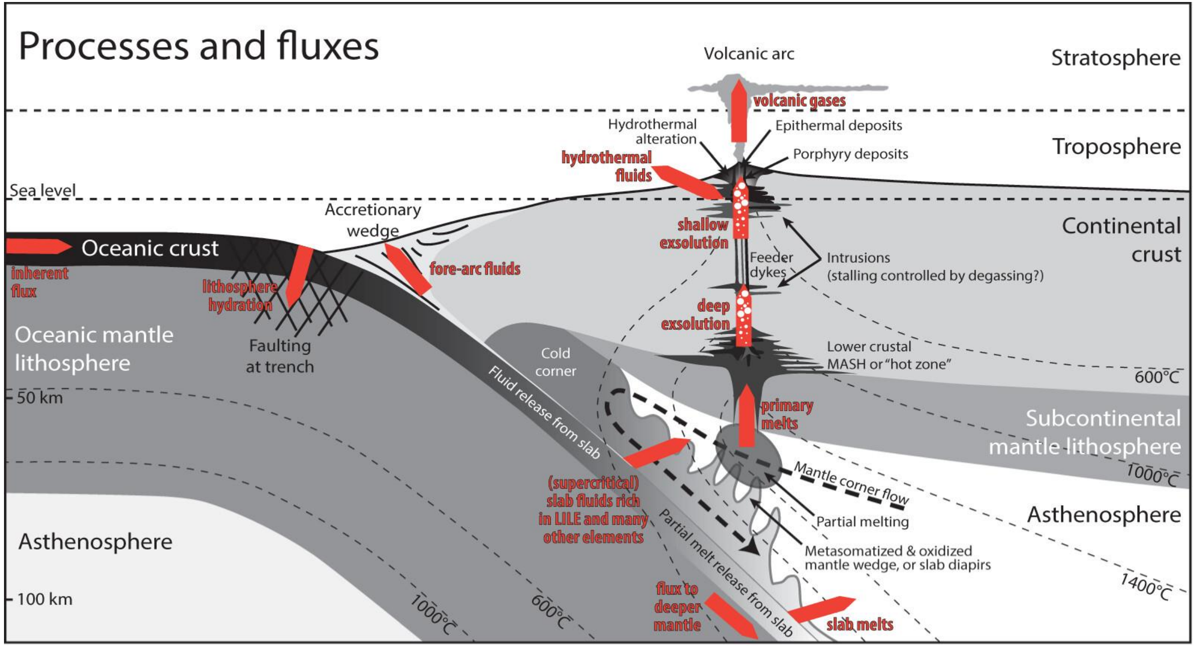


Nixon et al. 2015 *GSC OF7856*

“We anticipate demand for nickel in the next 30 years will be 200% to 300% of the demand in the previous 30 years”

Jess Farrell, BHP's asset president of Nickel West (2022)

Research rationale:
arc petrology and crust-mantle transfer



Zellmer et al. 2015 *GSL*

- **Volcanic rocks are modified** through differentiation, assimilation, and degassing of volatile-rich primary arc magmas

- **Complimentary study of high-T cumulates** is necessary for holistic understanding of arc magmatism and mantle-crust metal transfer

Primitive convergent margin (arc) intrusions

Primitive convergent margin (arc) intrusions

Alaskan-type intrusions:

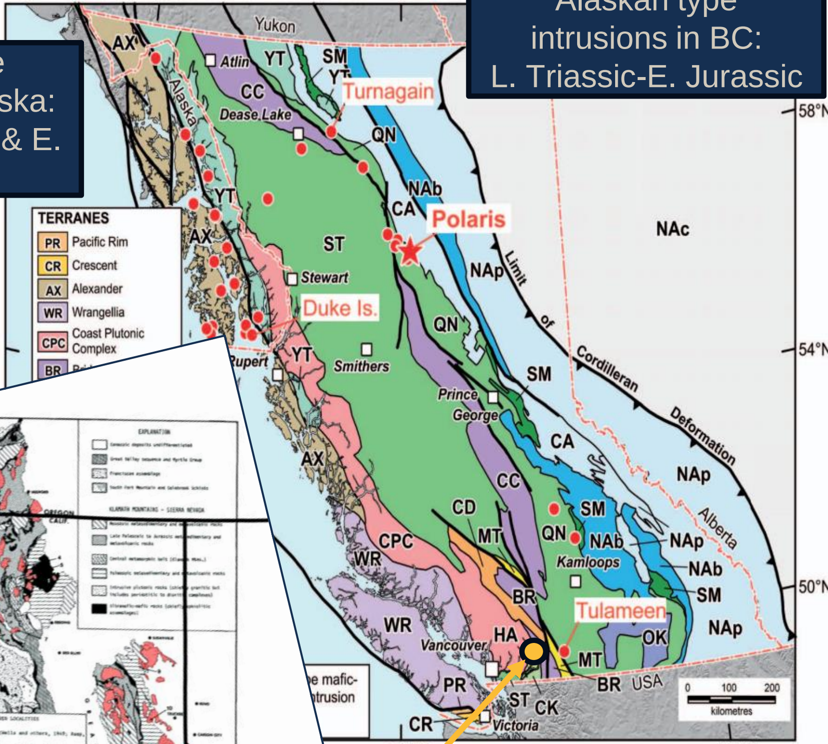
- Juvenile island arc terranes (Quesnellia, Stikinia, Yukon-Tanana): e.g., *ca.* 206-204 Ma Tulameen, *ca.* 187-186 Ma Polaris, *ca.* 189-185 Ma Turnagain (3381 kt Ni)

Giant Mascot-type intrusions:

- Continental arc (*ca.* 93 Ma Giant Mascot)

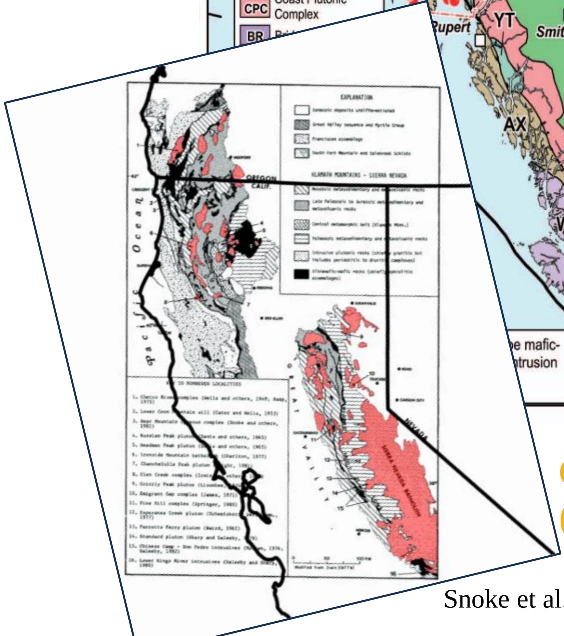
Alaskan type intrusions in Alaska: Siluro-Devonian & E. Cretaceous

Alaskan type intrusions in BC: L. Triassic-E. Jurassic



Milidragovic et al. 2021 *Can Min*

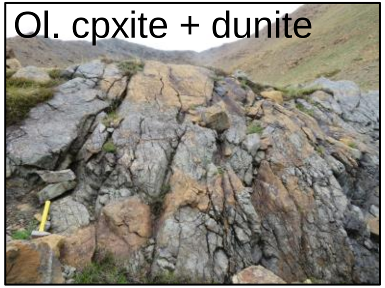
Giant Mascot (32,000 t Ni 1958-1974)



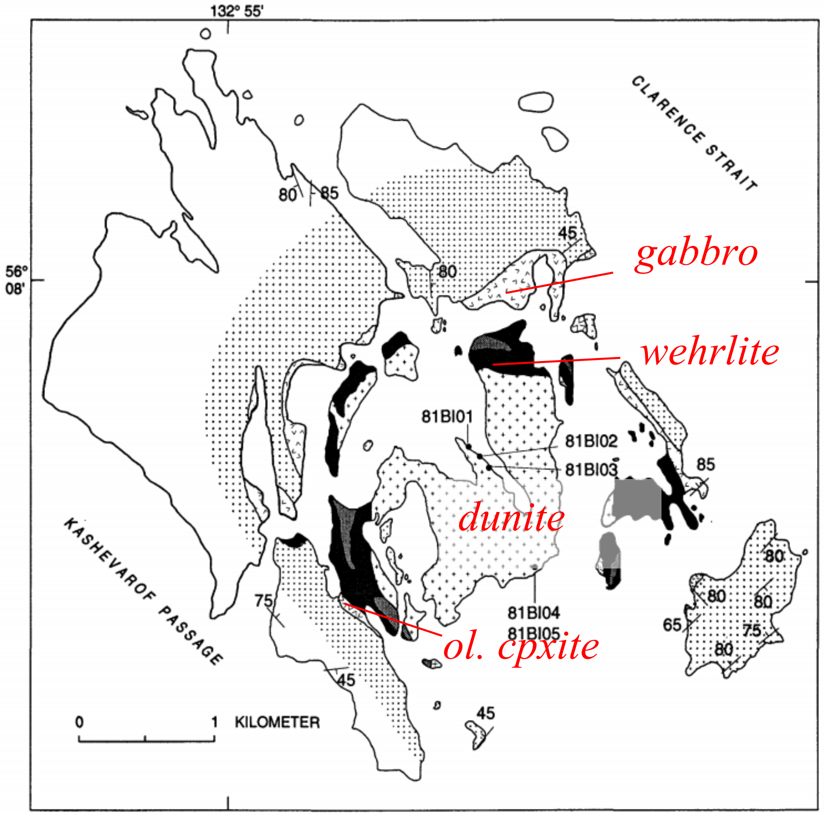
Snoke et al. 1982 *Geology*

Alaskan-type intrusions

Characteristic lithology



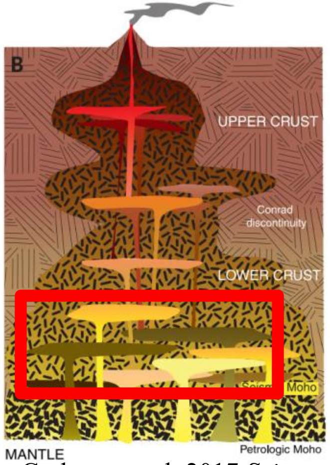
Concentrically zoned Blashke Island Alaskan-type intrusion



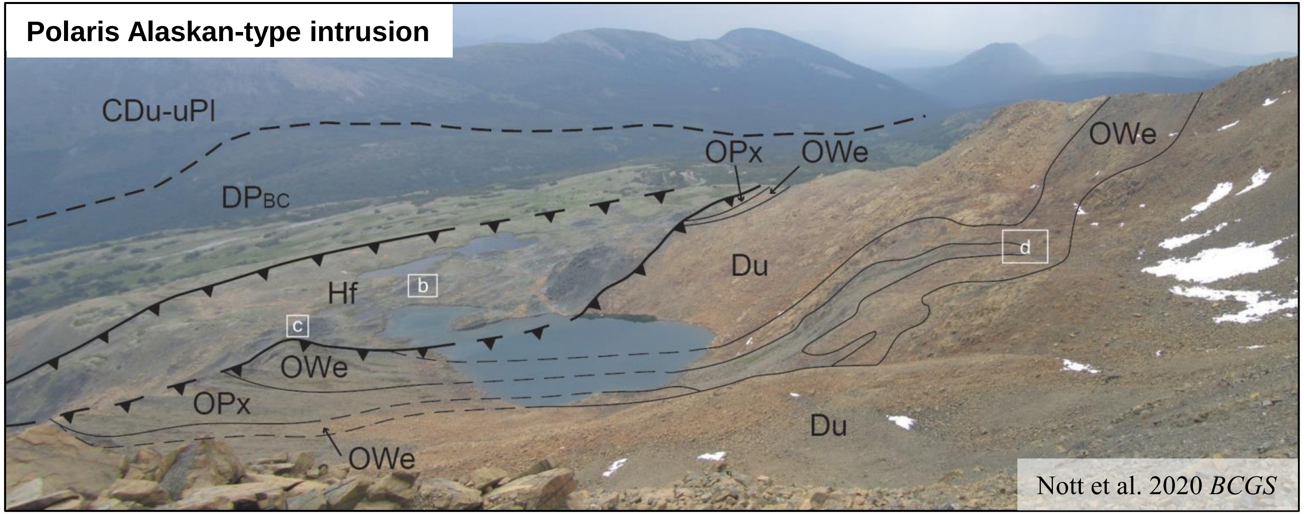
Himmelberg and Loney 1995 *USGS*

Alaskan-type intrusions

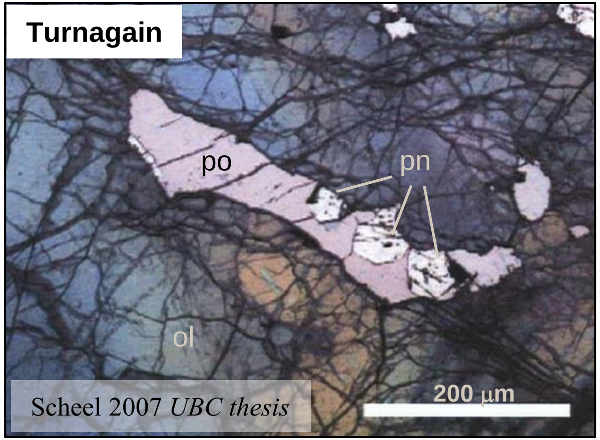
- Small (<18 km x 6 km), mantle-sourced, zoned, ultramafic-mafic bodies
- Transcrustal magma conduits/feeders to arc volcanos
- May contain magmatic mineralization
- Increasing importance of serpentinite (CO_2-mineralization +H_2)



Cashman et al. 2017 *Science*



Nott et al. 2020 *BCGS*



Scheel 2007 *UBC thesis*

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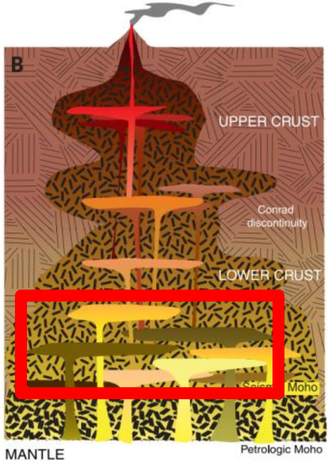
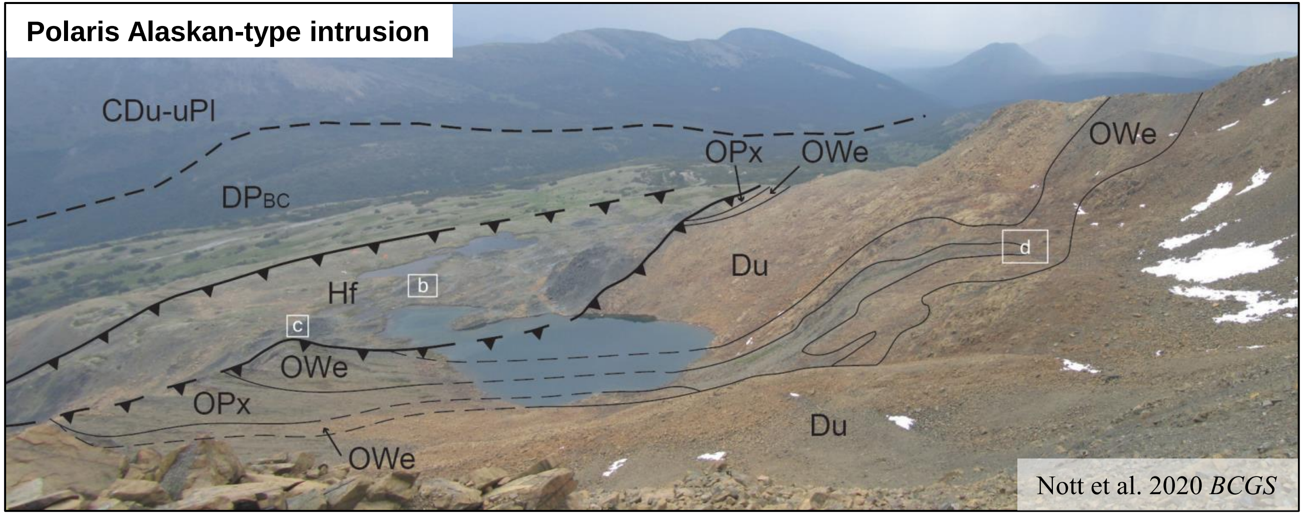


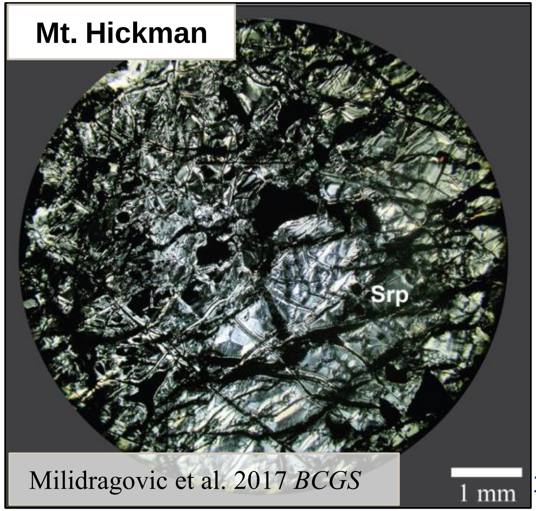
Cashman et al. 2017 *Science*

Polaris Alaskan-type intrusion



Nott et al. 2020 *BCGS*

Mt. Hickman



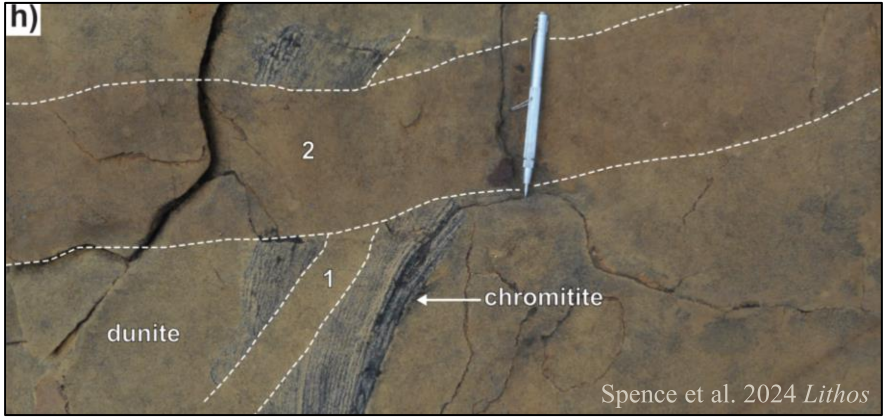
Milidragovic et al. 2017 *BCGS*

Alaskan-type intrusions: rock types

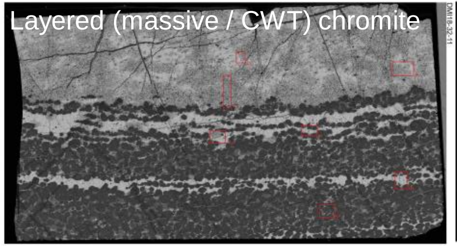
Dunite – Polaris intrusion

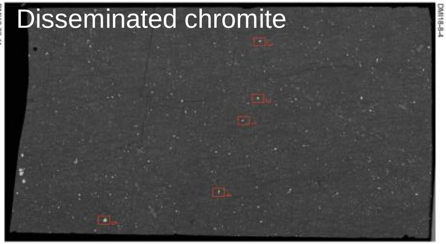
Spence et al. 2024 *Lithos*

Multiple dunite dike generations X-cutting layered chromite schlieren



BSE scans of dunite thin-sections

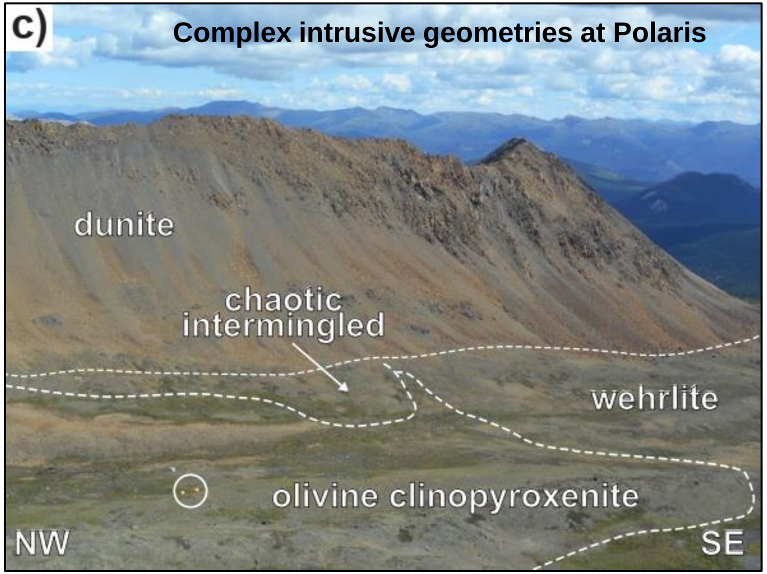




Milidragovic et al. 2024 *GSC OF 9201*

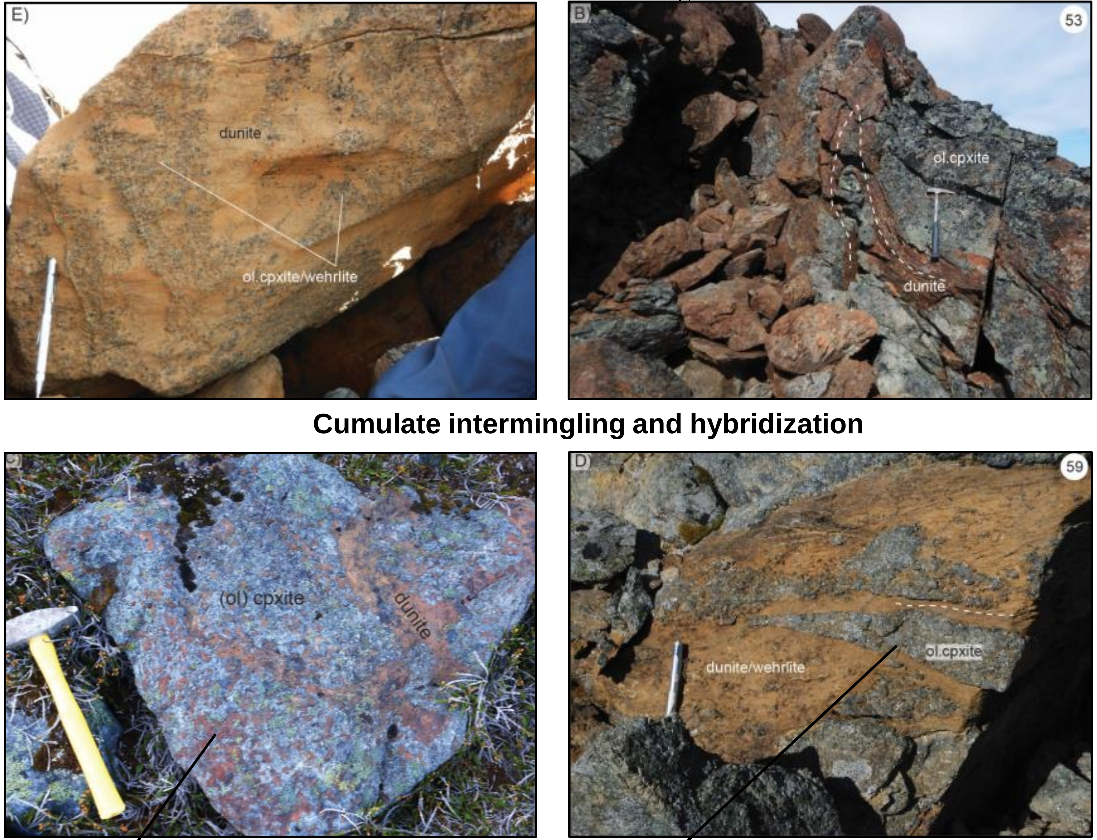
Alaskan-type intrusions: rock types

Milidragovic and Cleven 2023 *GSC OF 8946*



Spence et al. 2024 *Lithos*

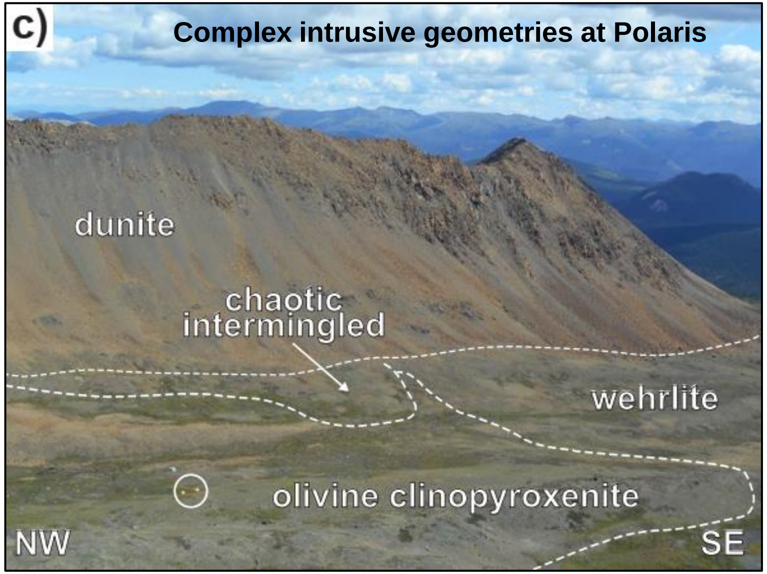
- Chaotic mixing, comingling, and hybridization at different T and rheological states



Mechanical disaggregation of dunite

Mechanical disaggregation of clinopyroxenite

Alaskan-type intrusions: rock types

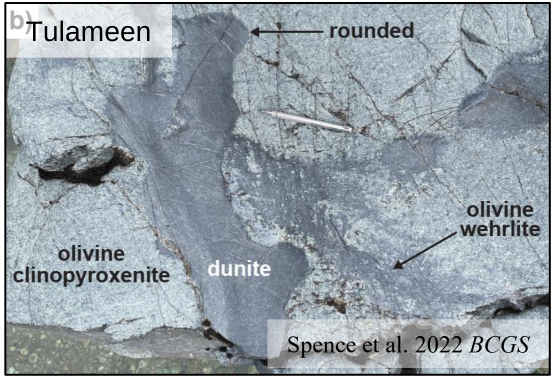


Spence et al. 2024 *Lithos*

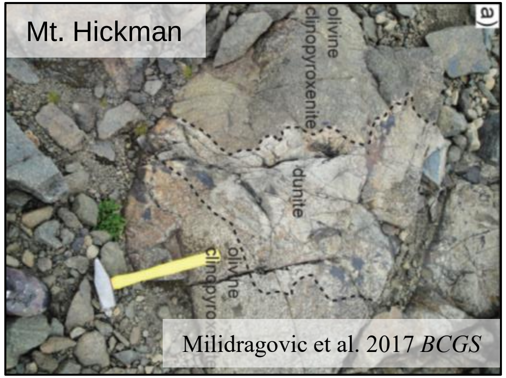
- Chaotic mixing, comingling, and hybridization at different T and rheological states

Milidragovic and Cleven 2023 *GSC OF 8946*

Cumulate intermingling and hybridization



Spence et al. 2022 *BCGS*

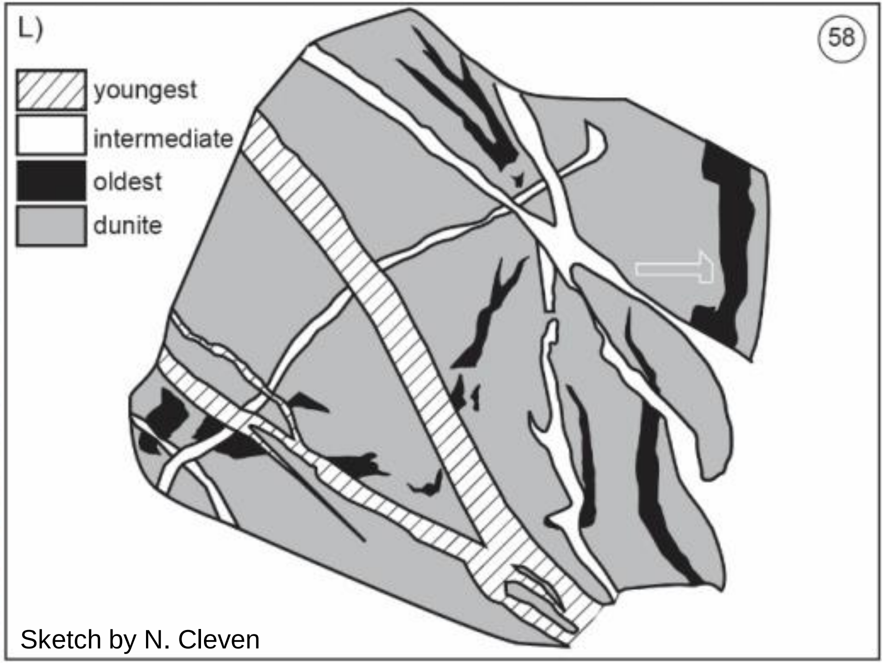


Milidragovic et al. 2017 *BCGS*

Alaskan-type intrusions: rock types

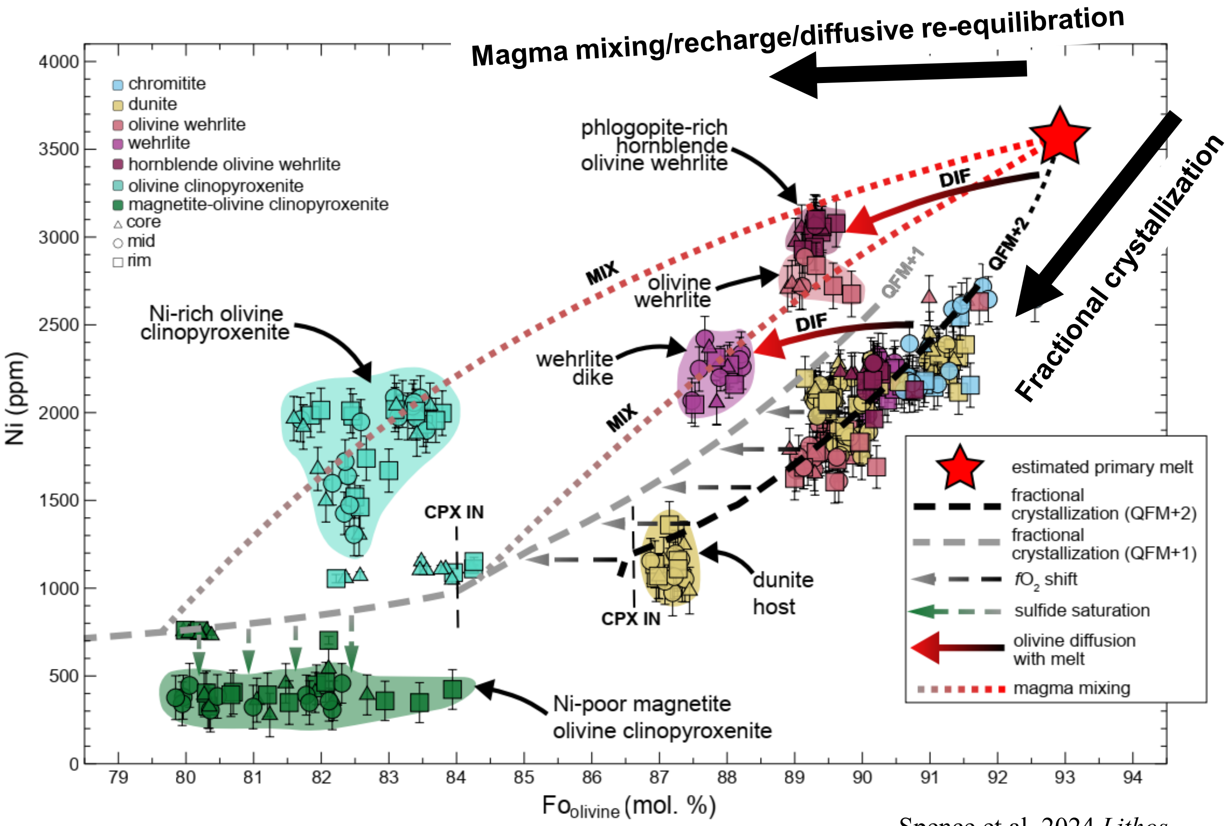
Episodic magma injection at the Lunar Creek Complex

Milidragovic and Cleven 2023 *GSC 8946*



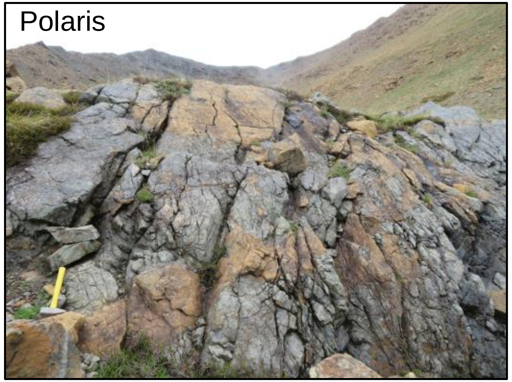
Sketch by N. Cleven

Alaskan-type intrusions: rock types

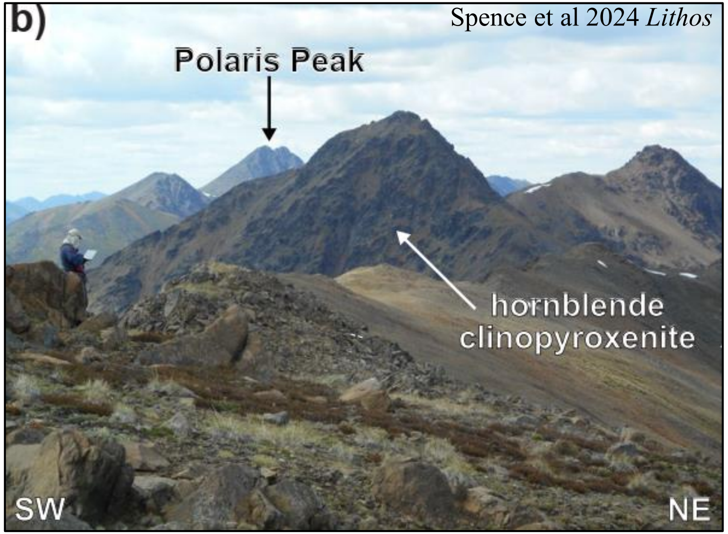


Spence et al. 2024 *Lithos*

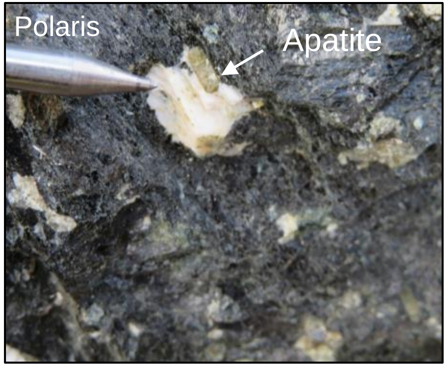
Cumulate intermingling and hybridization

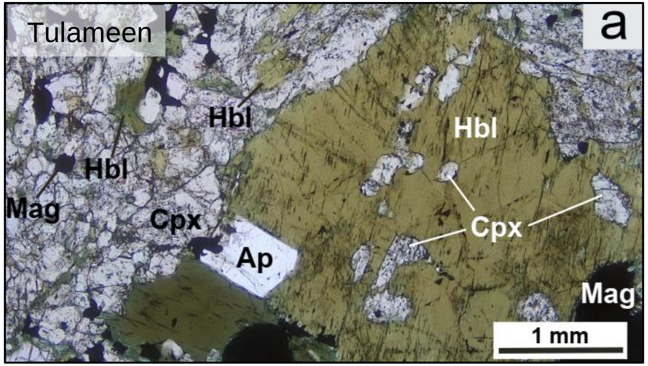


Alaskan-type intrusions: rock types



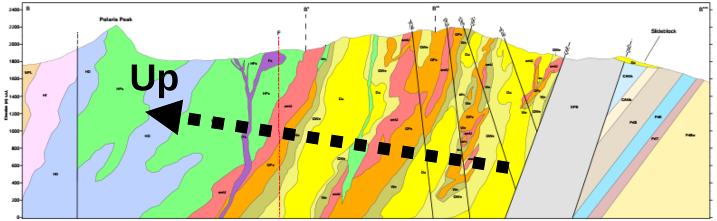
Nixon et al. in review *CMP*

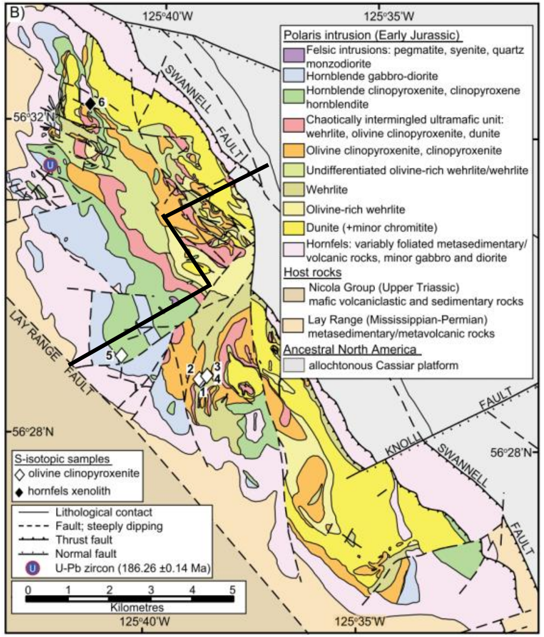




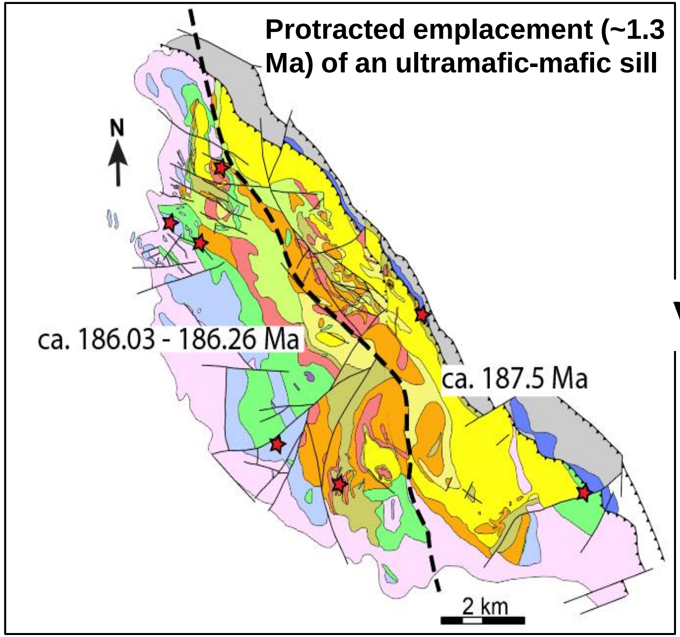
- Hornblende-rich evolved rocks
- Feldspathic pods with accessory minerals →evolved residual liquids that locally reached H_2O saturation (e.g., breccias)

Alaskan-type intrusions: multi-stage emplacement





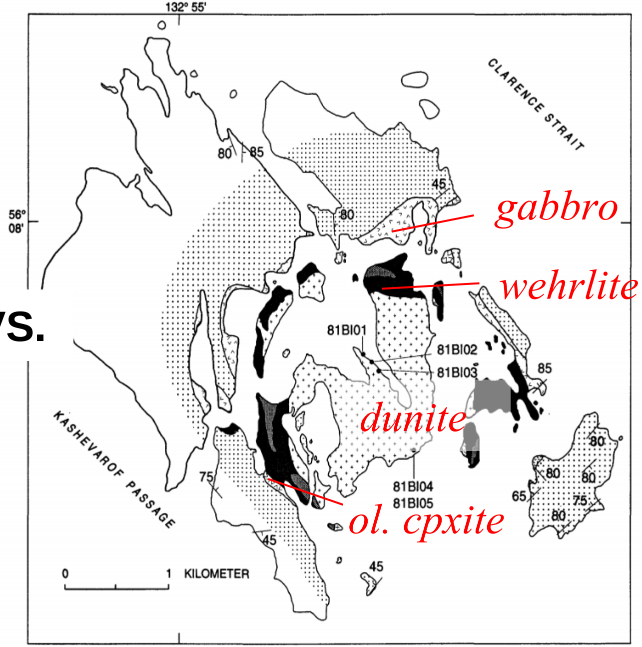
Milidragovic et al. 2023 *EPSL*



Restored geometry from Nott et al. 2020 *BCGS*

VS.

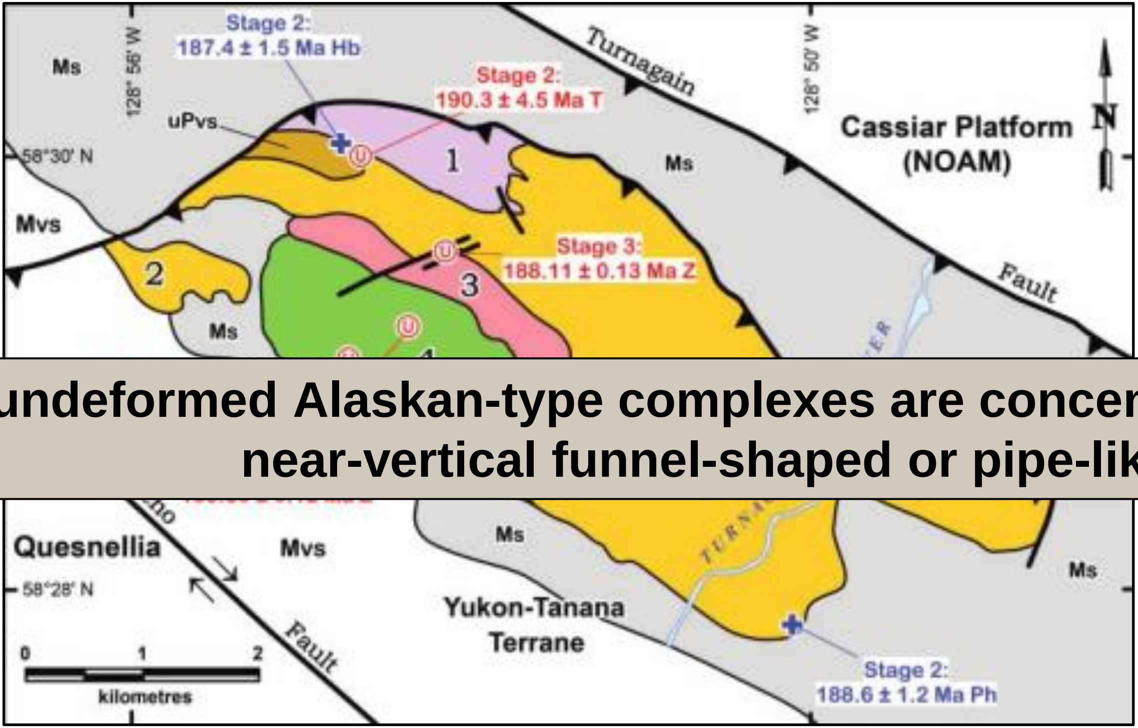
Concentrically zoned Blashke Island Alaskan-type intrusion



Himmelberg and Loney 1995 *USGS*

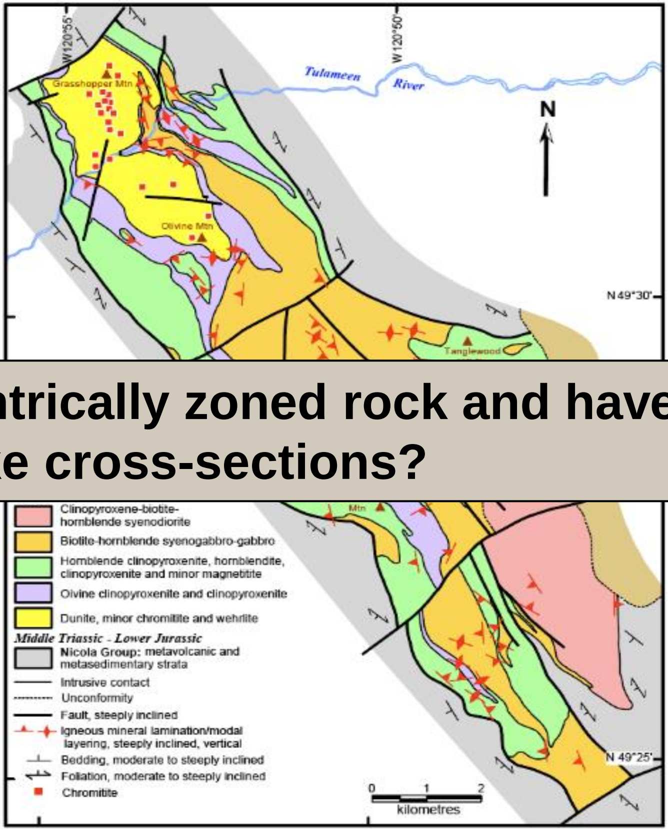
Alaskan-type intrusions: multi-stage emplacement

Turnagain



Nixon et al 2020 *CJES*

Tulameen



Nixon 2018 *BCGS*

undeformed Alaskan-type complexes are concentrically zoned rock and have near-vertical funnel-shaped or pipe-like cross-sections?

- CA-TIMS zircon ages support prolonged (~1-5 Ma), episodic emplacement

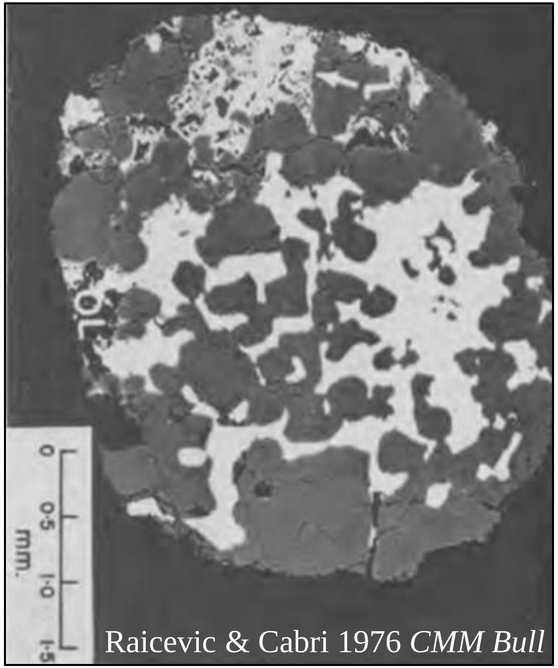
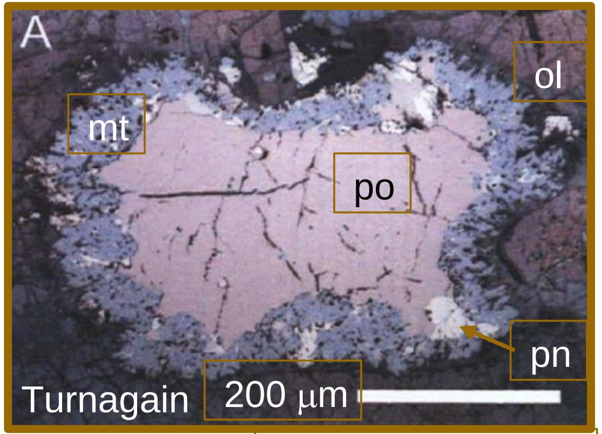


Fig. 1. Lithograph of a platinum nugget with olivine and octahedral chromite, from the Tulameen district, British Columbia. (Kemp 1902, *USGS* **in** Cabri et al. 2022 *Ore Geol Rev*)

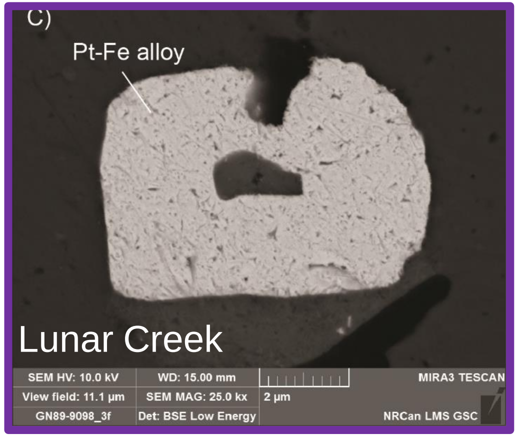
Magmatic mineralization in Alaskan-type intrusions

Magmatic mineralization

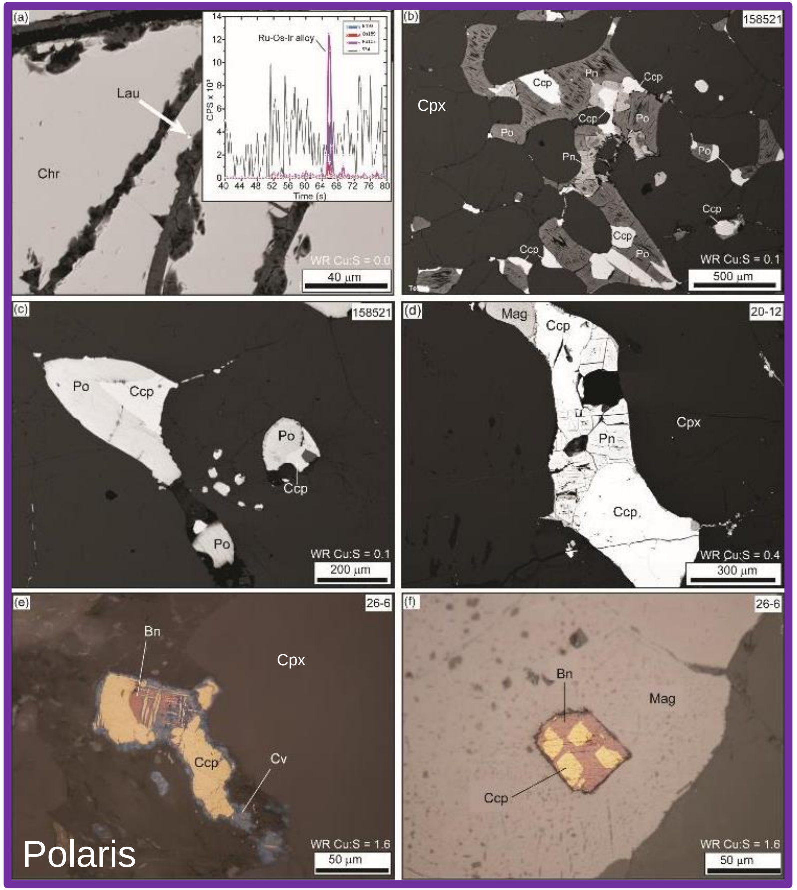
- 2 styles of mineralization
  - Early Ni (Cu-Co) sulfide mineralization (e.g., Turnagain)
  - Early PGM + late Cu-PPGE sulfide mineralization



Scheel 2007 *MSc thesis, UBC*



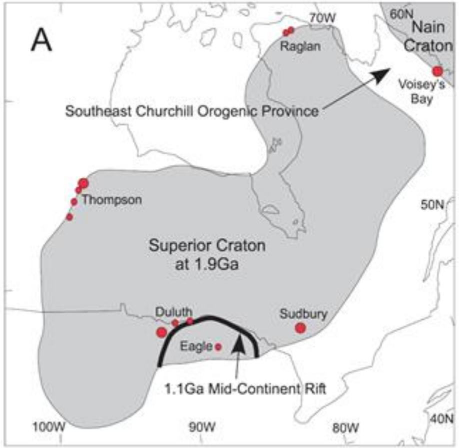
Milidragovic et al. 2024 *GSC OF9201*

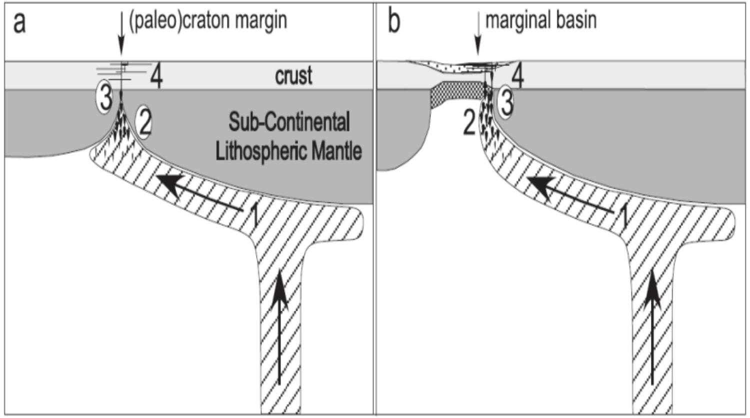


Milidragovic et al. 2021 Can Min

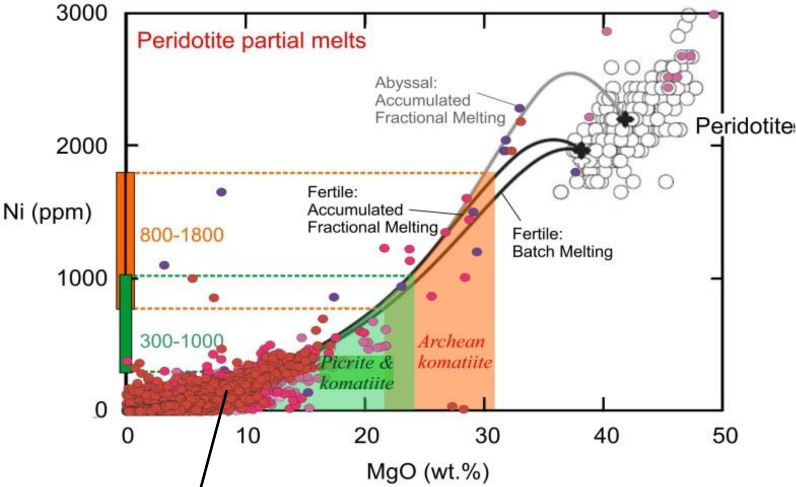
Conventional magmatic (sulfide) deposits

- Margins of ancient cratons where large degree mantle melts (LIP, plume) are focused into crust along trans-lithospheric pathways





Begg et al. 2010 *Econ Geol*



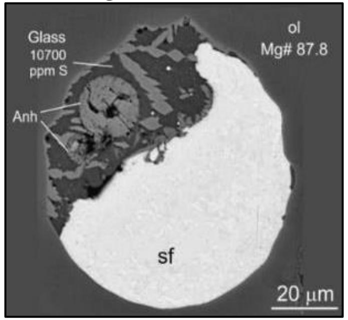
Modified from: Herzberg et al. 2010 *EPSL* and Herzberg 2011 *J Pet*

<u>Arc volcanics</u> *(n = 17,274)*

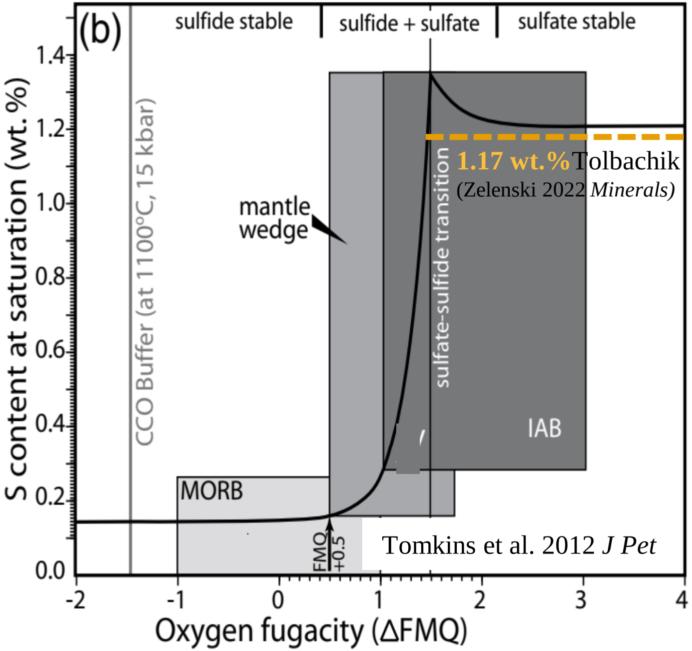
Izu-Bonin, Mariana, Honshu, Aleutian, Andes

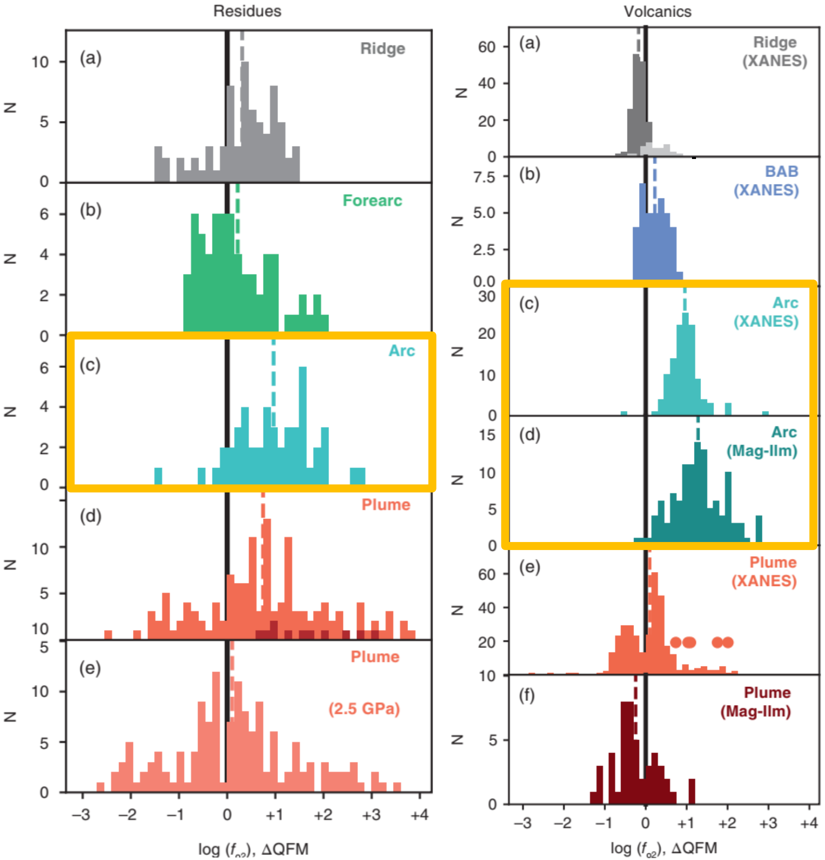
What is unconventional about arcs?

~FMQ+1.5



Zelenski et al. *2022 Minerals*



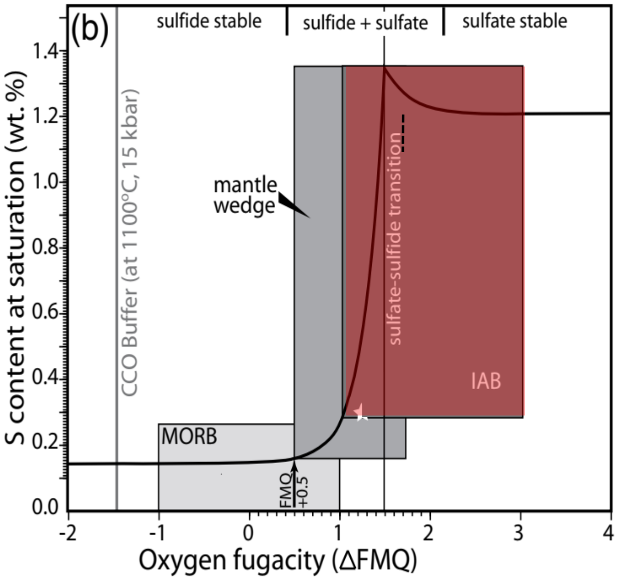


Cottrell et al. 2022 *Geophys Monogr*

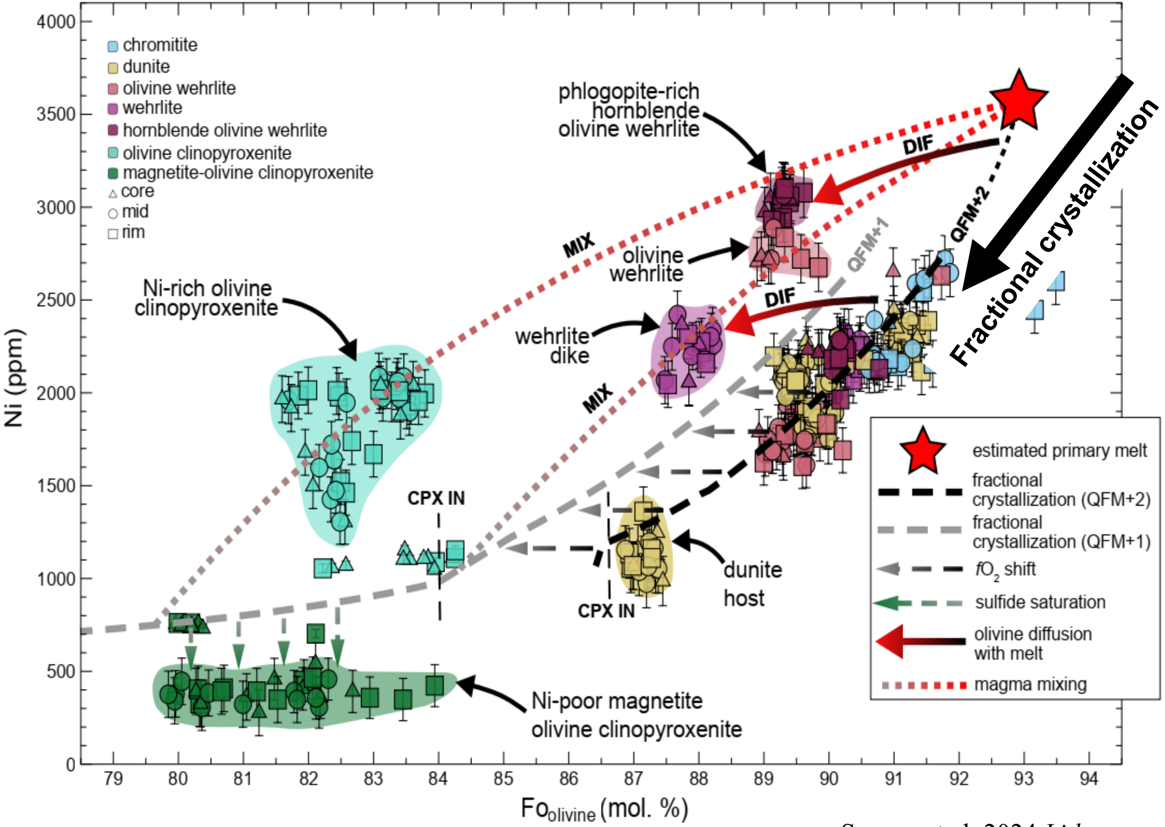
- Arc magmas are more oxidized than MOR/plume magmas!

Oxidation state of Alaskan-type intrusions

- Thermodynamic modelling of olivine fractionation paths for the Polaris intrusion suggest logfO_2 ~FMQ+2



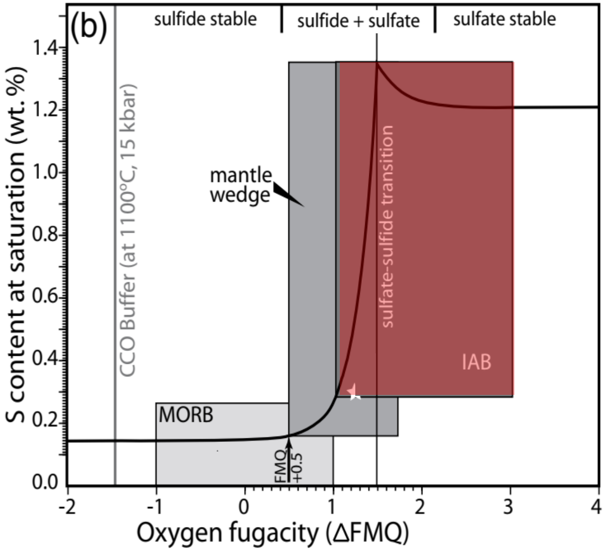
Tomkins et al. 2012 *J Pet*



Spence et al. 2024 *Lithos*

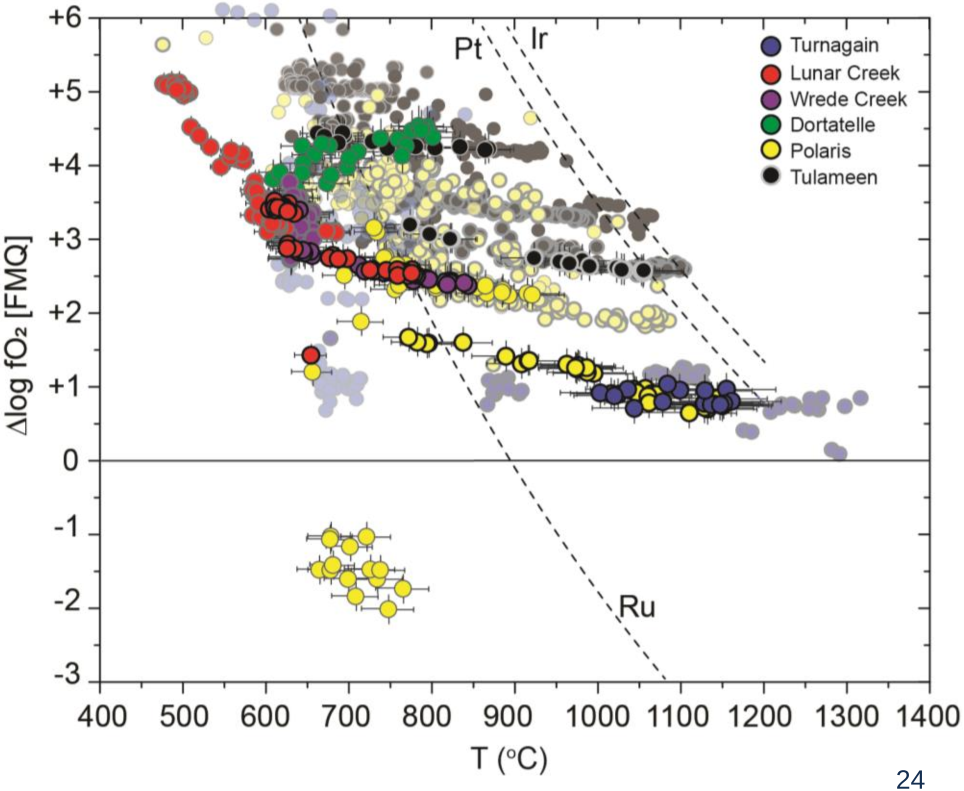
Oxidation state of Alaskan-type intrusions

- Moderately to strongly oxidized ($\log fO_2$ ≥FMQ+1)
- Systematic differences between intrusions
- Variability within individual intrusions



Tomkins et al. 2012 *J Pet*

Olivine-spinel fO_2-T equilibria based on Ballhaus et al. (1991) and data of Milidragovic et al. (2024), Scheel (2007), and Webb (2023)



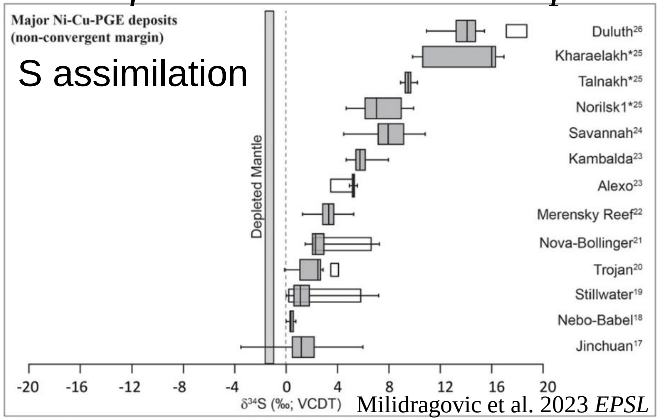
Crustal assimilation for early S-saturation

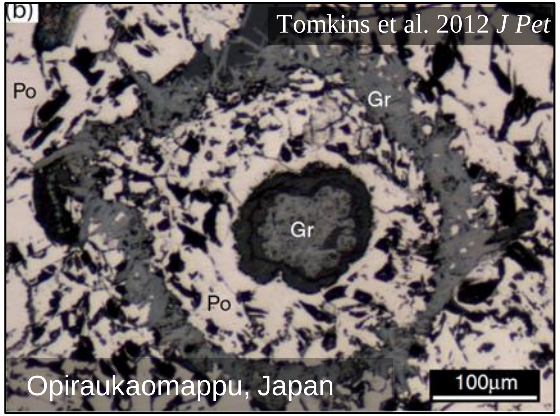
- Addition of S **and/or** reduction of oxidized ARC magma

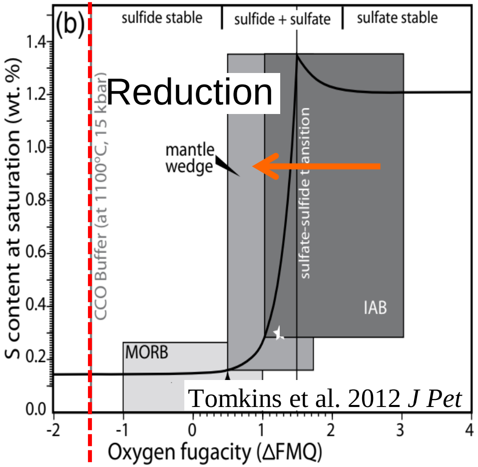
- Little reduced (graphite-bearing) assimilant needed

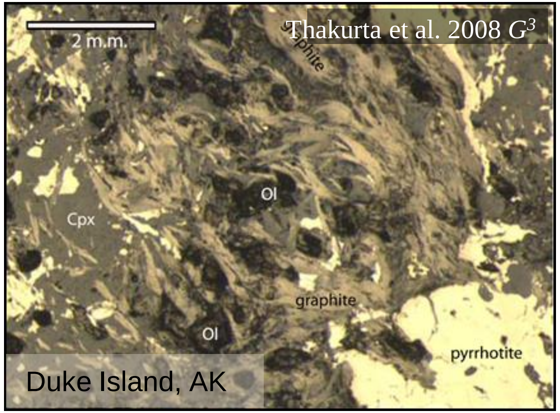
Necessary for development of Ni-sulfide deposits in arc settings! (e.g., Duke Island, Turnagain, Giant Mascot, Opiraukaomappu)

$^{34}S/^{32}S$ for select Ni-Cu-PGE deposits





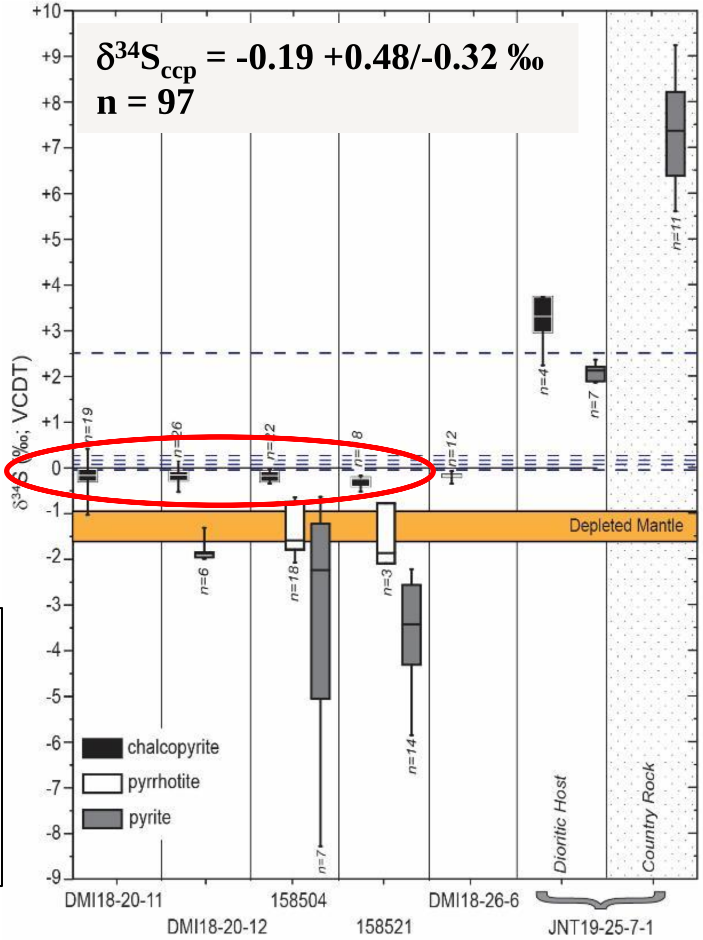


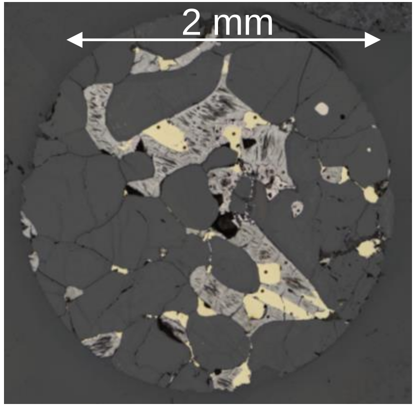


Mineralization in the absence of assimilation

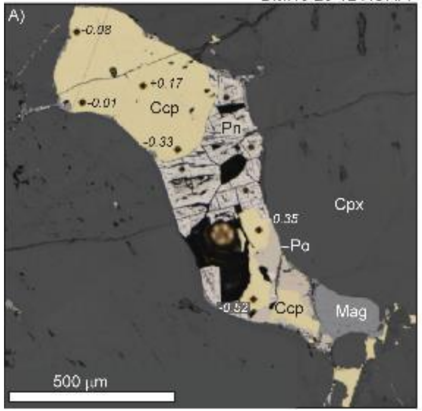
- Chalcopyrite is fresh and shows a narrow range of magmatic, near-chondric $\delta^{34}S$
- Other sulfides (po, py) reflect equilibration with oxidizing hydrothermal fluids
- Country rocks are strongly suprachondritic

Assimilation played a minor role - sulfur in Polaris magmas is largely magmatic!





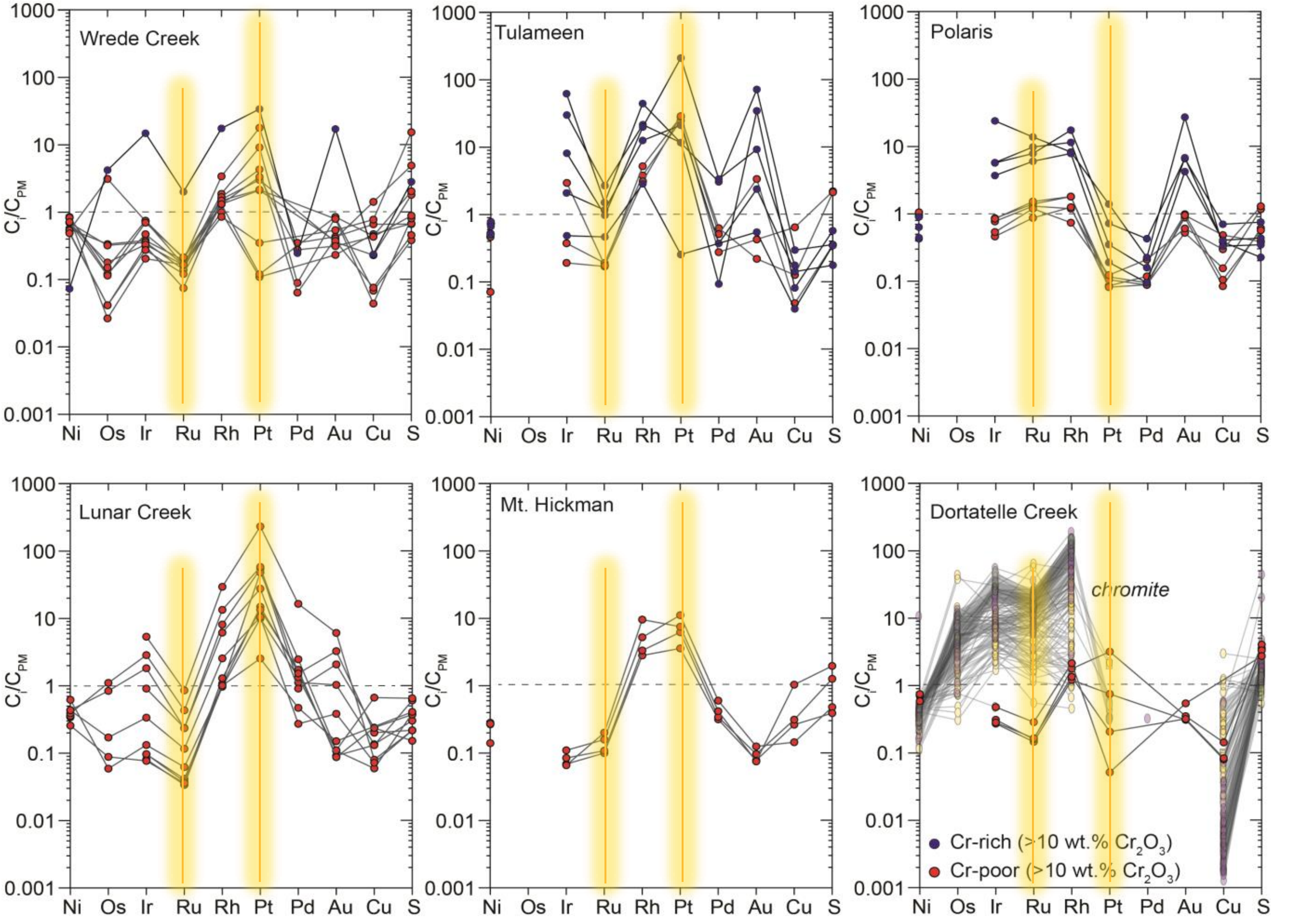
DMI18-20-12 ROI #1



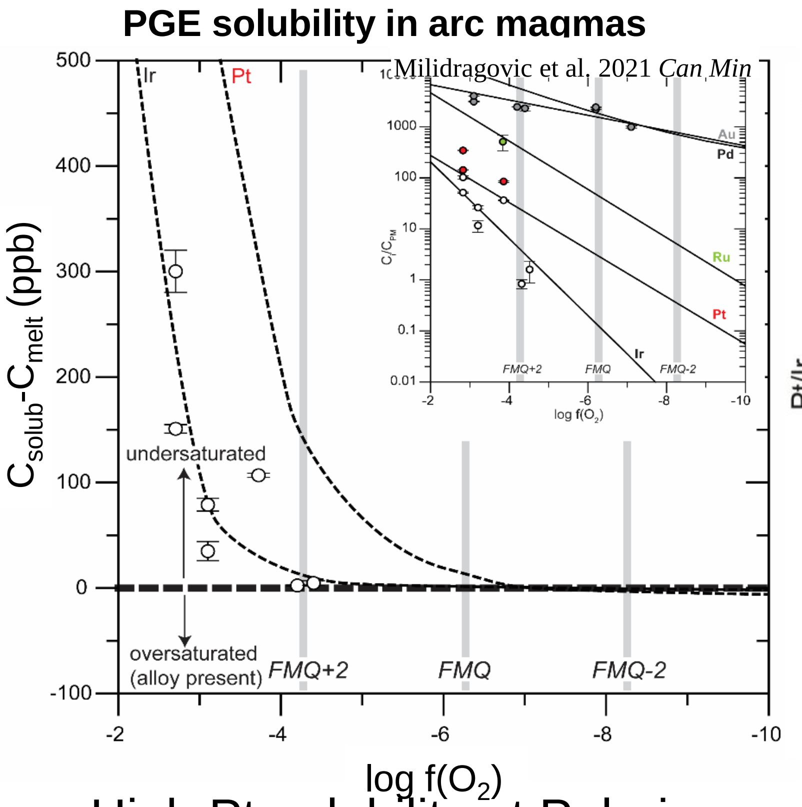
Milidragovic et al. 2023 *EPSL*

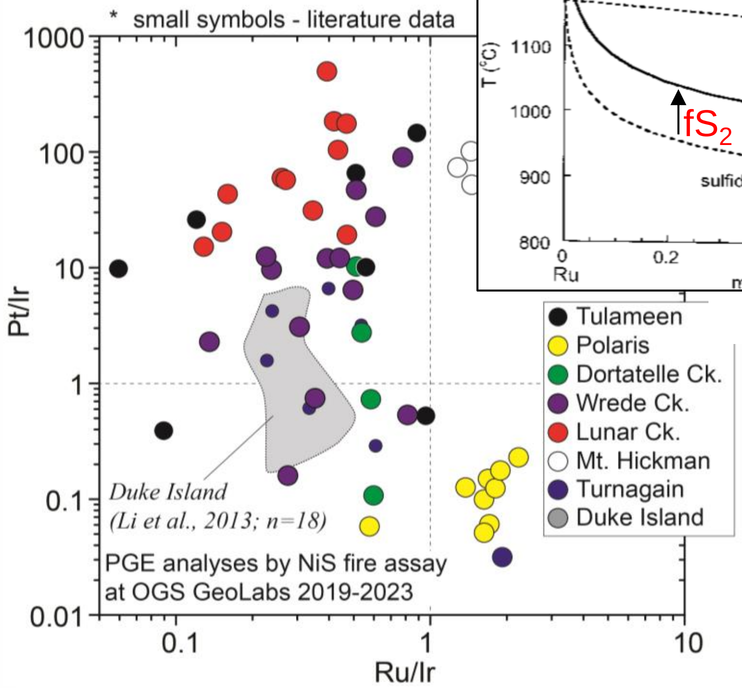
Mineralization in the absence of assimilation

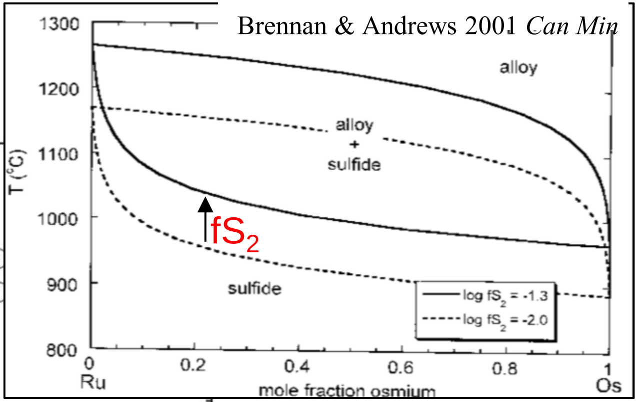
- Dunite-hosted, chromite-associated **PGE** mineralization (Pt-enriched, Ru-depleted vs. Pt-depleted, Ru-enriched)



Mineralization in the absence of assimilation

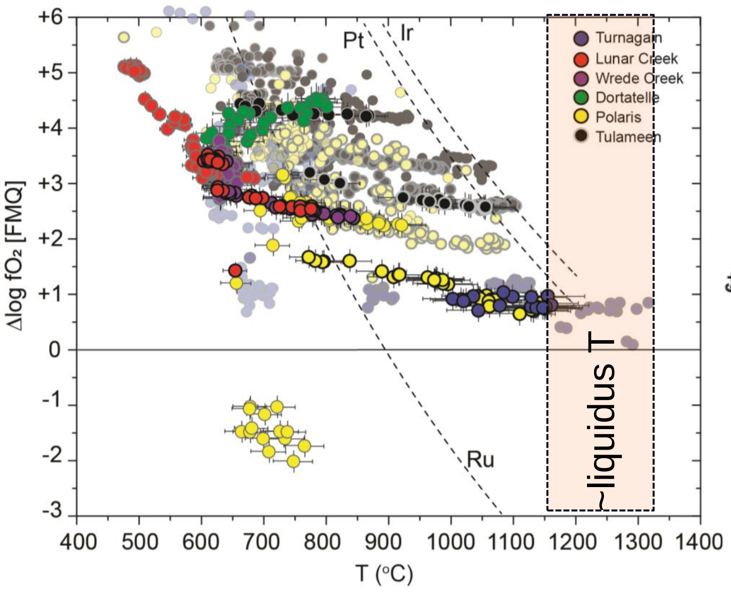


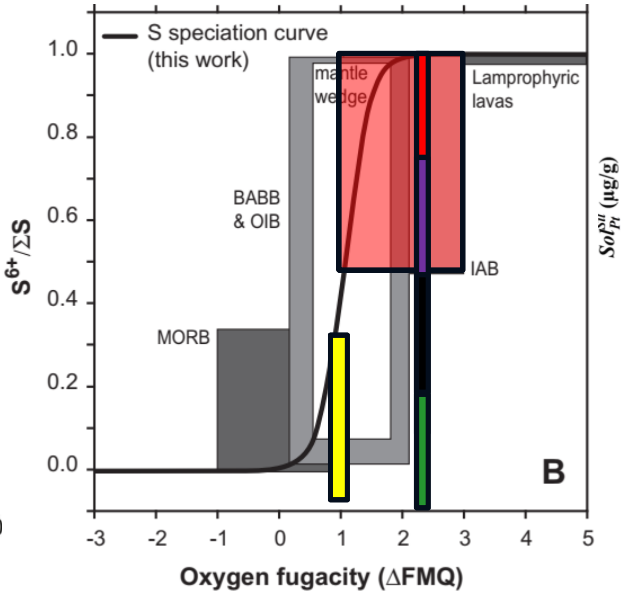




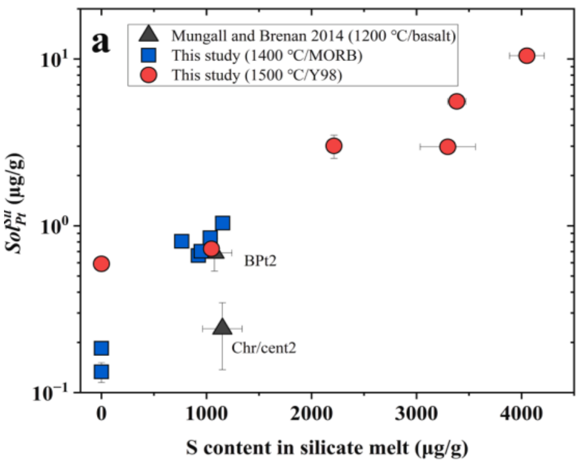
- High Pt-solubility at Polaris as result of high fO_2? (2021)
- High Ru/Ir at Polaris as result of “high” fS_2?

Mineralization in the absence of assimilation





Jugo et al. 2010 *GCA*



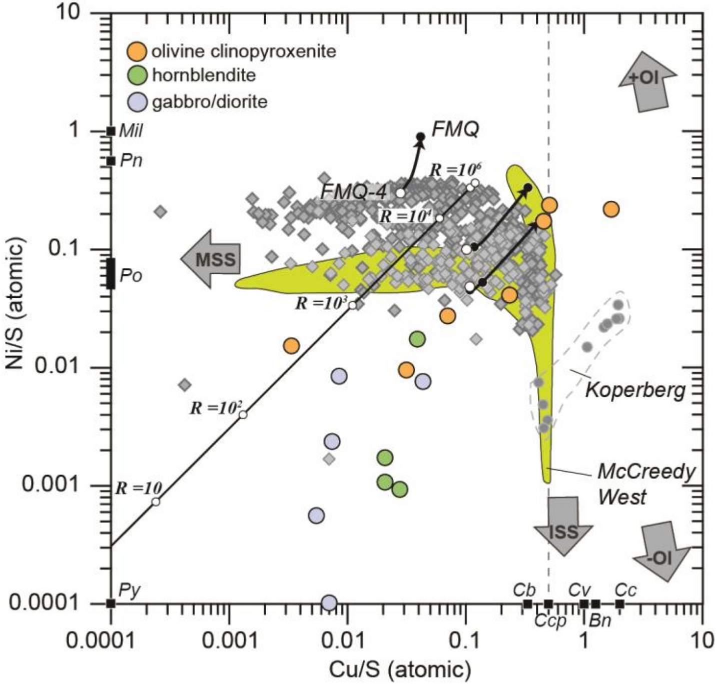
Wang & Li 2023 *GCA*

- At relatively low fO_2 (and high S^{2-}) of Polaris, Ru is stabilized at higher T while Pt is more soluble (e.g., Wang & Li., 2023)

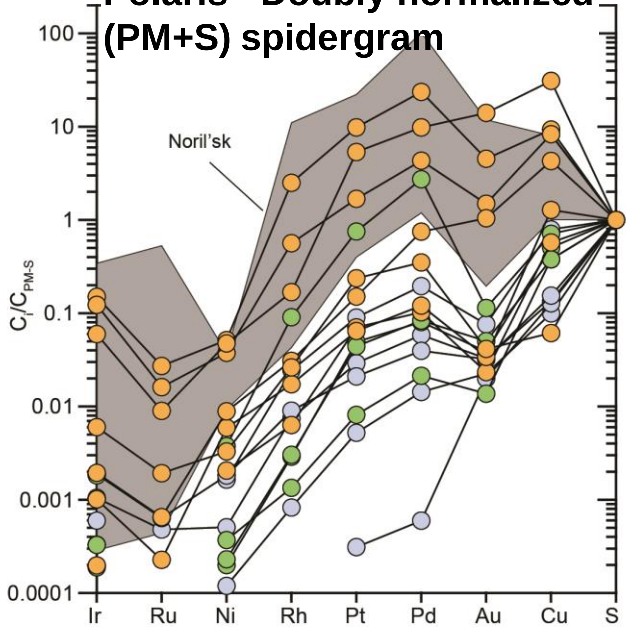
fO_2 of primitive Alaskan-type magmas governs fS_2 and PGE solubility

Mineralization in the absence of assimilation

- Cu-PPGE rich sulfides at Tulameen, Polaris and Turnagain
  - Cu-rich (ccp-bornite) assemblages
  - High Cu-PPGE tenors

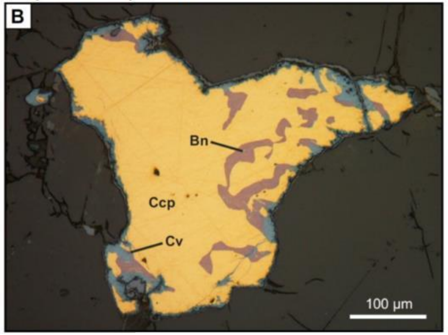


Polaris - Doubly normalized (PM+S) spidergram



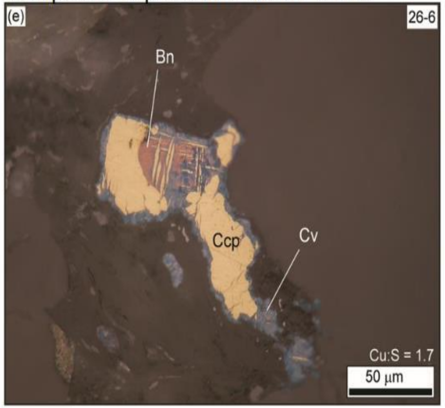
Milidragovic et al., 2021 *Can Min*

Composite Ccp-Bornite from Tulameen



Nixon et al 2020 *GSC OF8722*

Composite Ccp-Bornite from Polaris

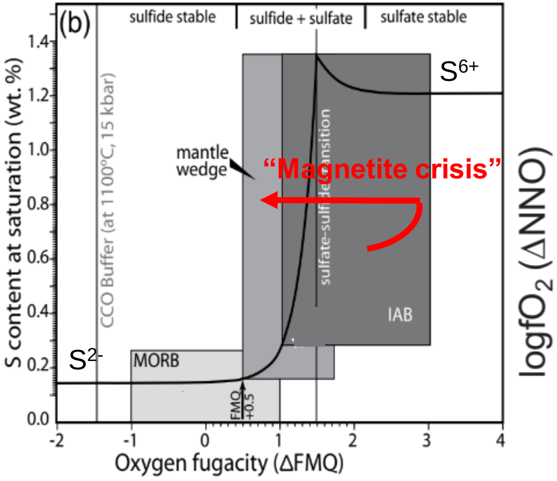


Milidragovic et al., 2021 *Can Min*

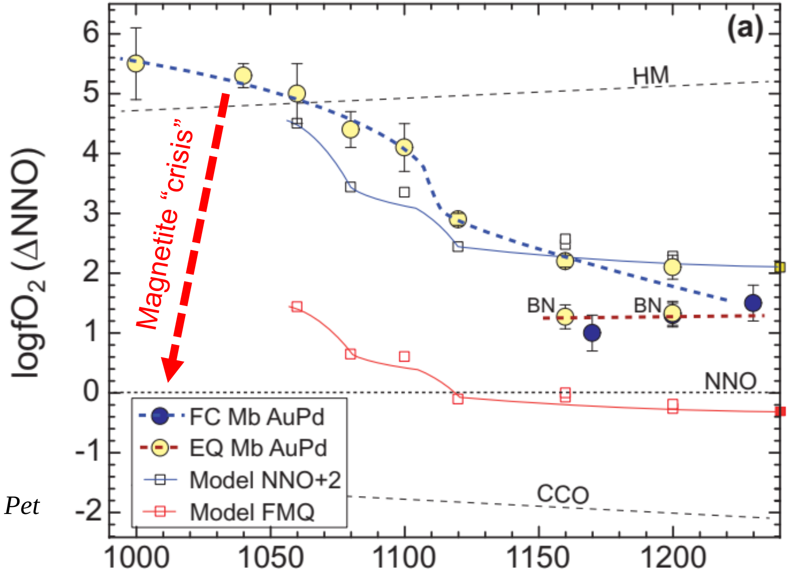
Mineralization in the absence of assimilation

- Hydrous primitive arc magmas undergo early **auto-oxidation** promoting S solubility (and increasing ΣS concentration)

- Evolved oxidized magma crystallizes **magnetite** (MgO ≤ 6 wt.%) and undergoes rapid reduction and sulfide supersaturation



Tomkins et al. 2012 *J Pet*



Ulmer et al. 2018 *J Pet*

Olivine $(Mg,Fe^{2+})_2SiO_4$
Orthopyroxene $(Mg,Fe^{2+})SiO_3$
Clinopyroxene $(Ca,Mg,Fe^{2+})Si_2O_6$

All low Fe^{3+}/Fe^{TOT} fO_2 ↑

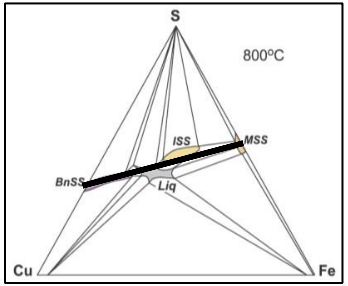
Magnetite $Fe^{3+}{}_2Fe^{2+}O_4$ fO_2 ↓

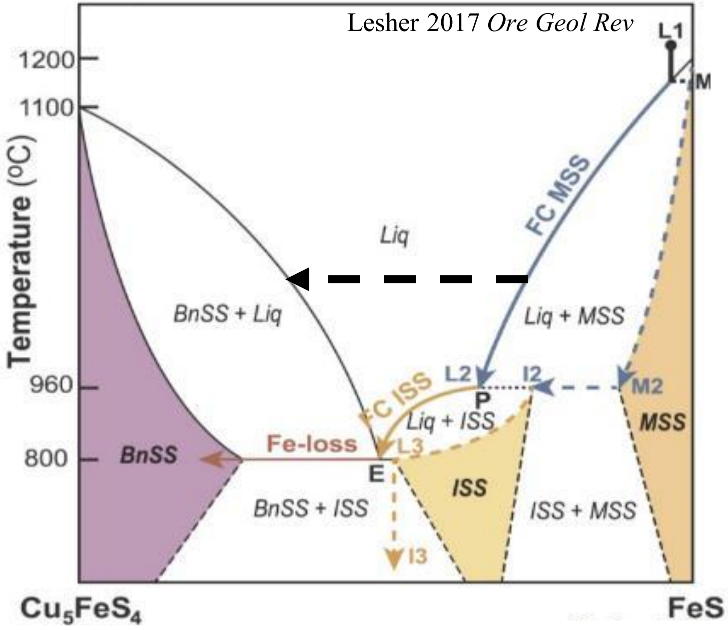
Mineralization in the absence of assimilation

- Cu (bornite)-rich early sulfides consistent with reduced FeS through oxidation

$$6(Fe^{2+}S)_{melt} + 4O_2 = 2(Fe^{2+}O \cdot Fe^{3+}{}_2O_3) + 3S^{2-}{}_2$$

- Ex., Polaris (BC), Champion zone at Tulameen (BC), DJ/DB zone at Turnagain (BC), experimental data



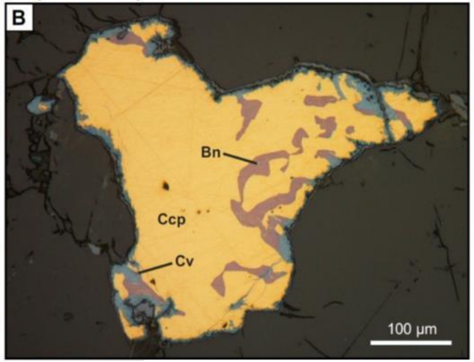


Lesher 2017 *Ore Geol Rev*

bornite

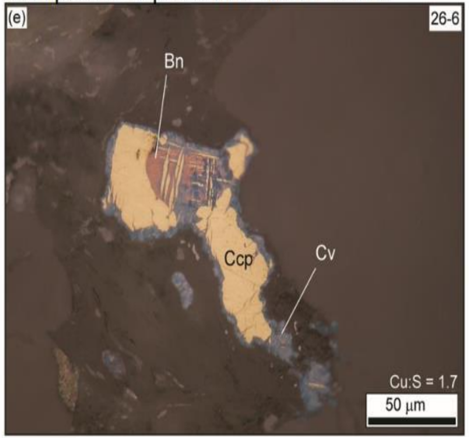
pyrrhotite

Composite Ccp-Bornite from Tulameen



Nixon et al 2020 *GSC OF8722*

Composite Ccp-Bornite from Polaris



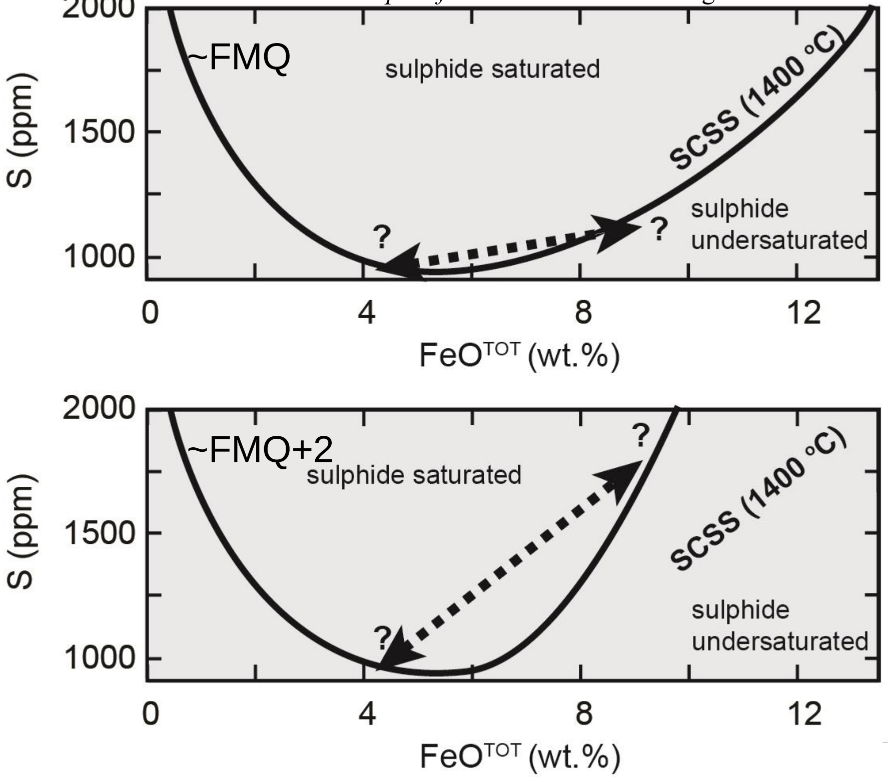
Milidragovic et al., 2021 *Can Min*

Mineralization in the absence of assimilation

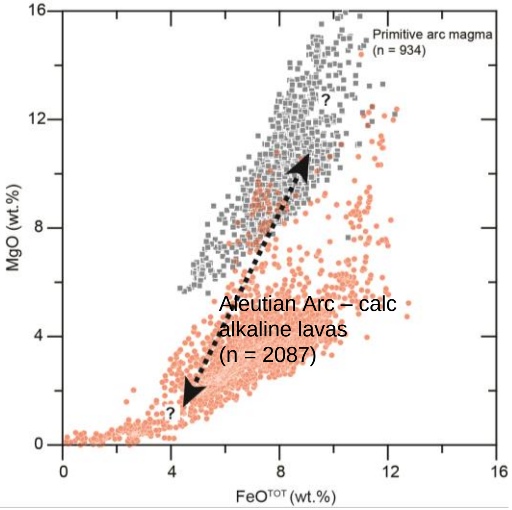
- Ubiquitous mixing between primitive and evolved magmas
- S-saturation through mixing between undersaturated melts possible due to U-shaped SCSS vs. FeO^{TOT}

U-Shaped SCSS vs FeO

Adapted from O'Neill and Mavrogenes 2002 *J Pet*

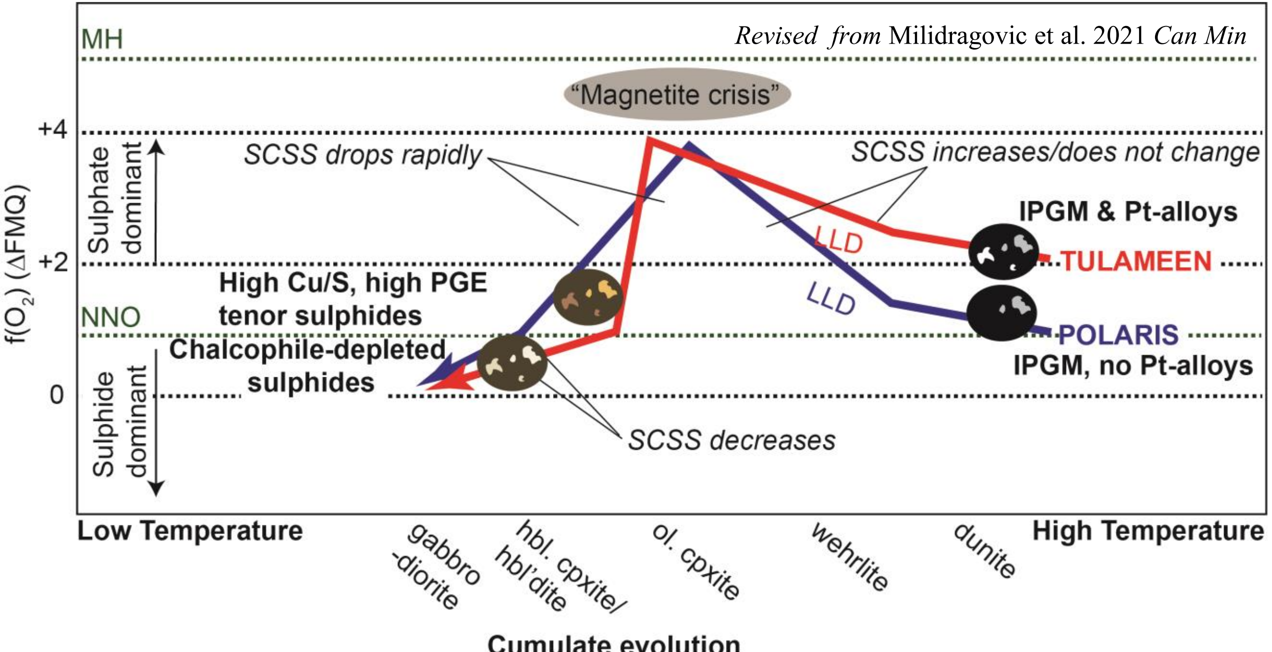


Cumulate intermingling and hybridization



Mineralization in Alaskan-type intrusions: Petrological synthesis

- Exogenous (assimilation of wall rock) – early dunite-hosted Ni-(Cu-Co) sulfide mineralization
- Endogenous – early dunite-hosted PGM mineralization + later clinopyroxenite-hosted Cu-PPGE sulfide mineralization



Conclusions

- Alaskan-type intrusions are dynamic, multi-episodic transcrustal magmatic systems
- Different primary fO_2, fS_2 (sub-arc mantle history), and different degrees of assimilation of variably reducing or S-rich rocks → different mineralization styles

Polaris ca. 1988

THANK YOU!

Tsay Keh Dene First Nation, Takla First Nation, Chu Cho Environmental, Silverking Helicopters, Apex Geoscience, Benchmark Metals (Thesis Gold), D. Petts, M. Beauchamp, D. Schumann, R. Stern

TGI supported work

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ARTICLE

Syn-accretionary multistage assembly of an Early Jurassic Alaskan-type intrusion in the Canadian Cordillera: U–Pb and $^{40}Ar/^{39}Ar$ geochronology of the Turnagain ultramafic–mafic intrusive complex, Yukon–Tanana terrane

Graham T. Nixon, J. Erik Scheel, James S. Scoates, Richard M. Friedman, Corey J. Wall, Janet Gabites, and Sarah Jackson-Brown

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Sulfate recycling at subduction zones indicated by sulfur isotope systematics of Mesozoic ultramafic island arc cumulates in the North American Cordillera

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REDOX-CONTROLLED CHALCOPHILE ELEMENT GEOCHEMISTRY OF THE POLARIS ALASKAN-TYPE MAFIC-ULTRAMAFIC COMPLEX, BRITISH COLUMBIA, CANADA

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Olivine in ultramafic rocks from the Polaris Alaskan-type intrusion: A geochemical record of open-system crystallization, diffusional re-equilibration, mantle source, and redox conditions in primitive arc magmas

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