

# Mineralogical, textural, and geochemical parameters of the Ni-Co-(PGE) Crawford Deposit, Abitibi greenstone belt, Superior Province, Ontario, Canada

N. Carter<sup>1</sup> and P. Jugo<sup>1</sup>

<sup>1</sup>Mineral Exploration Research Centre (MERC), Harquail School of Earth Sciences, Laurentian University, 935 Ramsey Lake Rd., Sudbury, ON, P3E 2C6, Canada



Laurentian University  
Université Laurentienne

HARQUAIL School of Earth Sciences  
École des sciences de la Terre

## ABSTRACT

The 2704 ± 0.88 Ma Crawford deposit, located 50 km north of Timmins, is part of a mafic-ultramafic intrusion hosted within the volcanic rocks of the Stoughton-Roquemaure Assemblage in the Abitibi greenstone belt. Nickel occurs in the deposit as disseminated pentlandite, heazlewoodite, and awaruite in a dunite-to-peridotite body, showing progressive stages of serpentinization. The deposit is separated into two zones by a steep regional N-NW sinistral strike-slip fault: the Main-West zone on the western side and the East zone on the eastern side. This research project characterized the effects of serpentinization on the present mineral assemblages and extracted mineralogical and geochemical parameters that may assist in locating and evaluating similar deposits in the district and elsewhere. Ninety-one samples were collected during the summers of 2022 and 2023 from eight drill holes that included dunite, peridotite, pyroxenite, and gabbro. Detailed optical petrography characterized the preserved primary olivine and pentlandite and the secondary heazlewoodite, awaruite, and magnetite with their associated textural relationships. A subset of 12 samples have been analyzed by electron probe microanalysis (EPMA) to quantify the forsterite and nickel content in olivine and the composition of the sulfide and alloy assemblages in the deposit.

Petrographic results show that the dunites comprise ellipsoidal and prismatic acumulate olivine with less than 5% pyroxene and chromite. The Main-West zone exhibits progressive serpentinization, ranging from approximately 20% to 100%, transforming primary olivine into serpentine and pentlandite to heazlewoodite, awaruite, and magnetite. In contrast, samples of the East zone are completely serpentinized and contain heazlewoodite, magnetite, and limited pentlandite. Crawford samples with preserved olivine, regardless of degree of serpentinization, have Ni from 2,000 up to 3,500 ppm with a median value of 2,700 ± 400 ppm at Fo<sub>88 ± 2</sub>. EPMA of sulfides and alloys yield Fe<sub>4.5</sub>Ni<sub>4.3</sub>S<sub>8</sub> for pentlandite (Fe:Ni close to 1:1), Ni<sub>2</sub>Fe for awaruite, and stoichiometric heazlewoodite of Ni<sub>3</sub>S<sub>2</sub>. The mineralogical changes and the variability in the EPMA imply loss of sulfur during serpentinization, mobilization of Fe, Ni, and Cu, and upgrading of nickel tenor in the sulfide-alloy assemblages.

## REGIONAL AND DEPOSIT-SCALE GEOLOGY

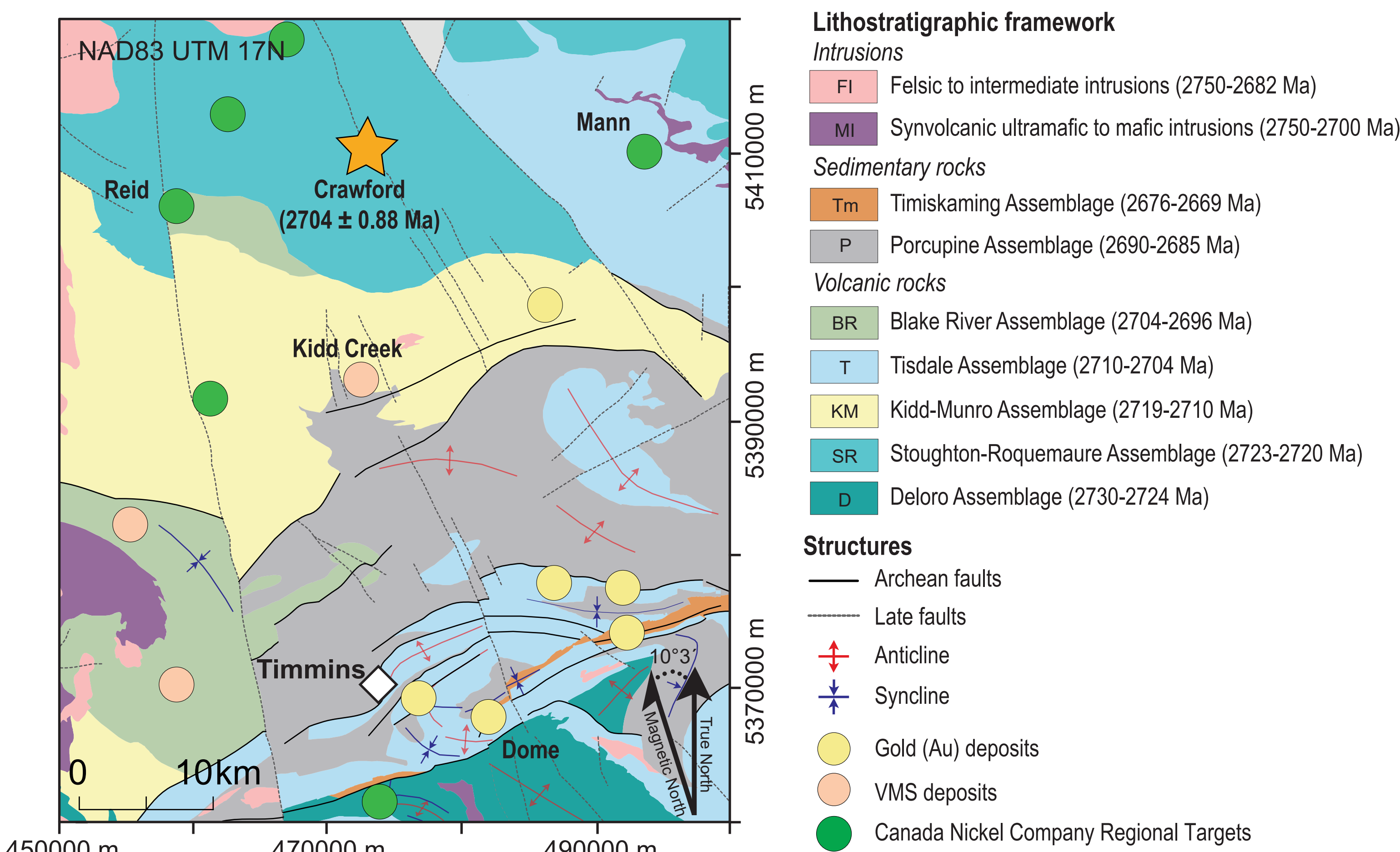


Figure 1. Regional geology of the study area simplified from Adetunji et al. (submitted 2024). The location of the Crawford deposit is indicated with a star symbol.

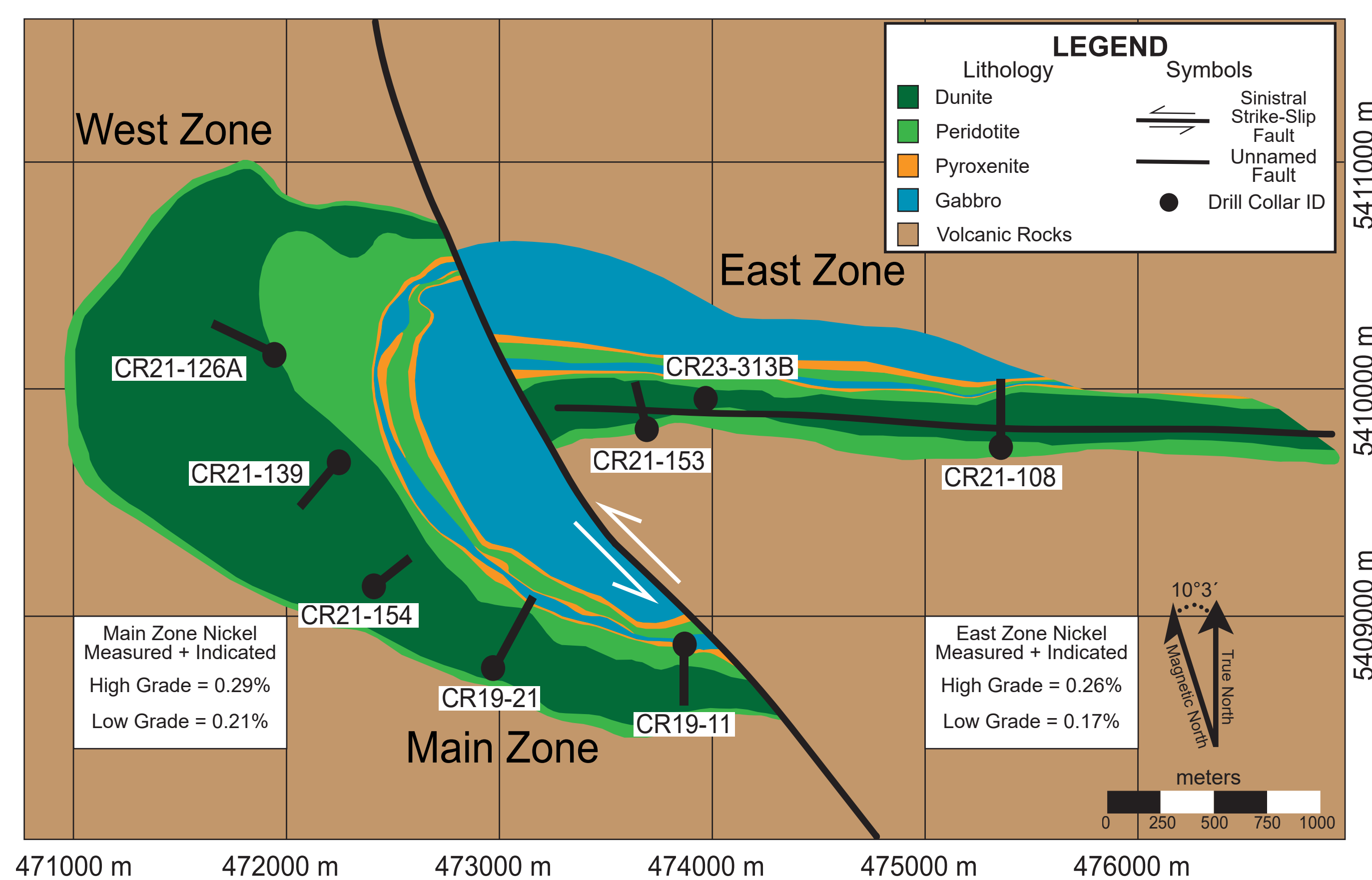


Figure 2. Geological map of the Crawford mafic-ultramafic intrusive complex and host volcanic rocks of the Stoughton-Roquemaure Assemblage. The locations of the eight sampled drill holes and the surface projection of their trajectory are indicated. The main and east zones measured and indicated nickel grades are shown. Simplified from Ausenco Engineering Canada ULC (NI 43-101 report, 2023).

## ALTERATION

Serpentinization is the most common type of hydrothermal alteration of ultramafic rocks, resulting in a suite of secondary minerals dominated by serpentine. At Crawford, the degree of serpentinization appears to be related to proximity to faults in the system. This is summarized in Fig. 3, which shows olivine almost unaltered in sample CR21-139 (west side of the intrusion in Fig. 2) and a progressive increase in the degree of serpentinization (Figs. 3B to 3D). The process is texturally non-destructive; the outline of the olivine grains pseudomorph to serpentine are well-preserved.

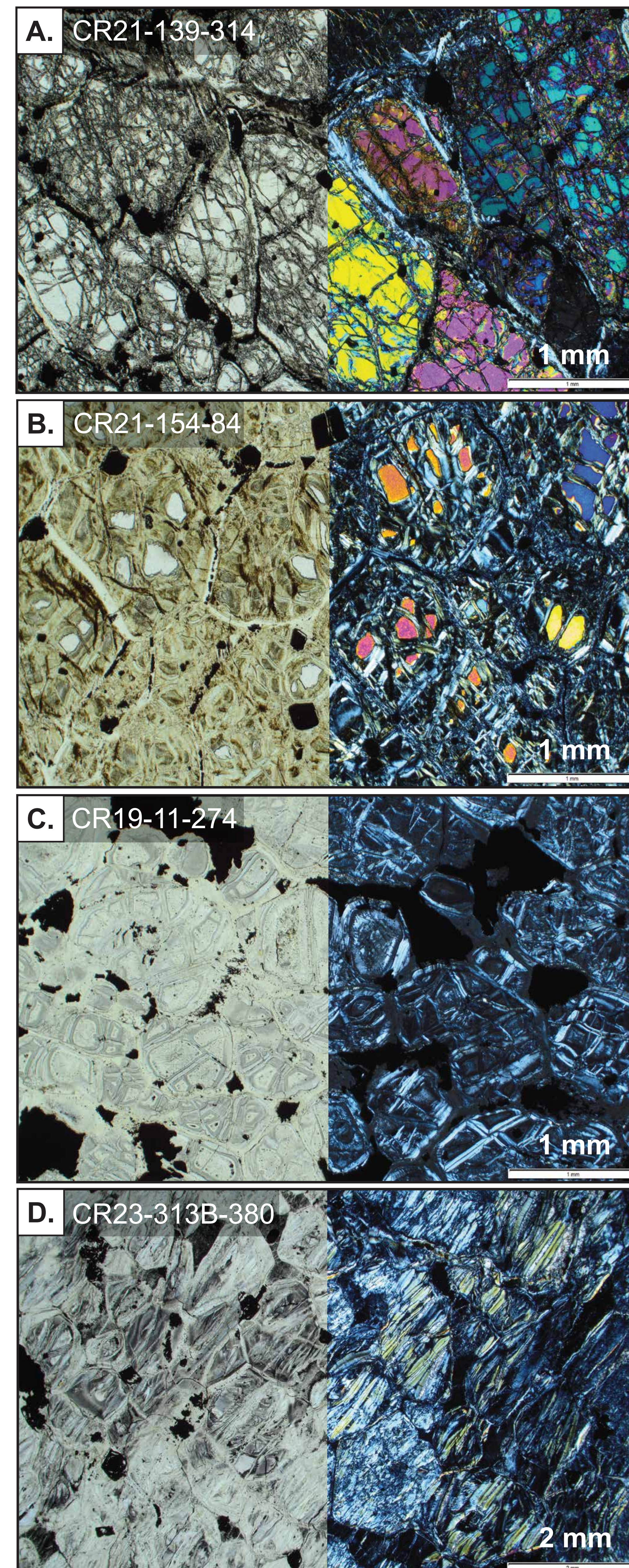


Figure 3. Composite plane-polarized and cross-polarized photomicrographs of increasingly serpentinized dunite samples showing olivine gradually replaced by serpentine (top to bottom). A. Large prismatic fractured olivine grains with minor paracrystalline serpentine. B. Ellipsoidal olivine partly pseudomorphs to serpentine. C. Complete hourglass serpentine pseudomorphs after olivine. D. Transgranular serpentine after olivine.

Figure 4 shows the progressive serpentinization of the sulfide assemblages. Serpentinization commonly decreases oxygen and sulfur fugacities ( $fO_2$  and  $fS_2$ ), favouring the formation of sulfide minerals with higher cation/sulfur (e.g., heazlewoodite) or Fe-Ni alloys (e.g., awaruite) and native metals (e.g., native copper). Magnetite is a common secondary mineral, and oxygen is expected to leave the system (Abdel-Halim, 2023). A decrease in  $fO_2$  is attained by the decomposition of  $H_2O$ , where oxygen is used to produce  $Fe^{3+}$  (in magnetite) from  $Fe^{2+}$  (in olivine), increasing  $H_2$  content and creating reducing conditions (Eckstrand, 1975). The continued hydrogen production during serpentinization would extract S from primary sulfides as  $H_2S$  (Klein and Bach, 2009). For example, pentlandite destabilization favours the formation of heazlewoodite and awaruite, leading to the upgrade of Ni tenor in the alteration assemblages (Evans et al., 2023).

## SULFIDE-ALLOY-OXIDE TEXTURES

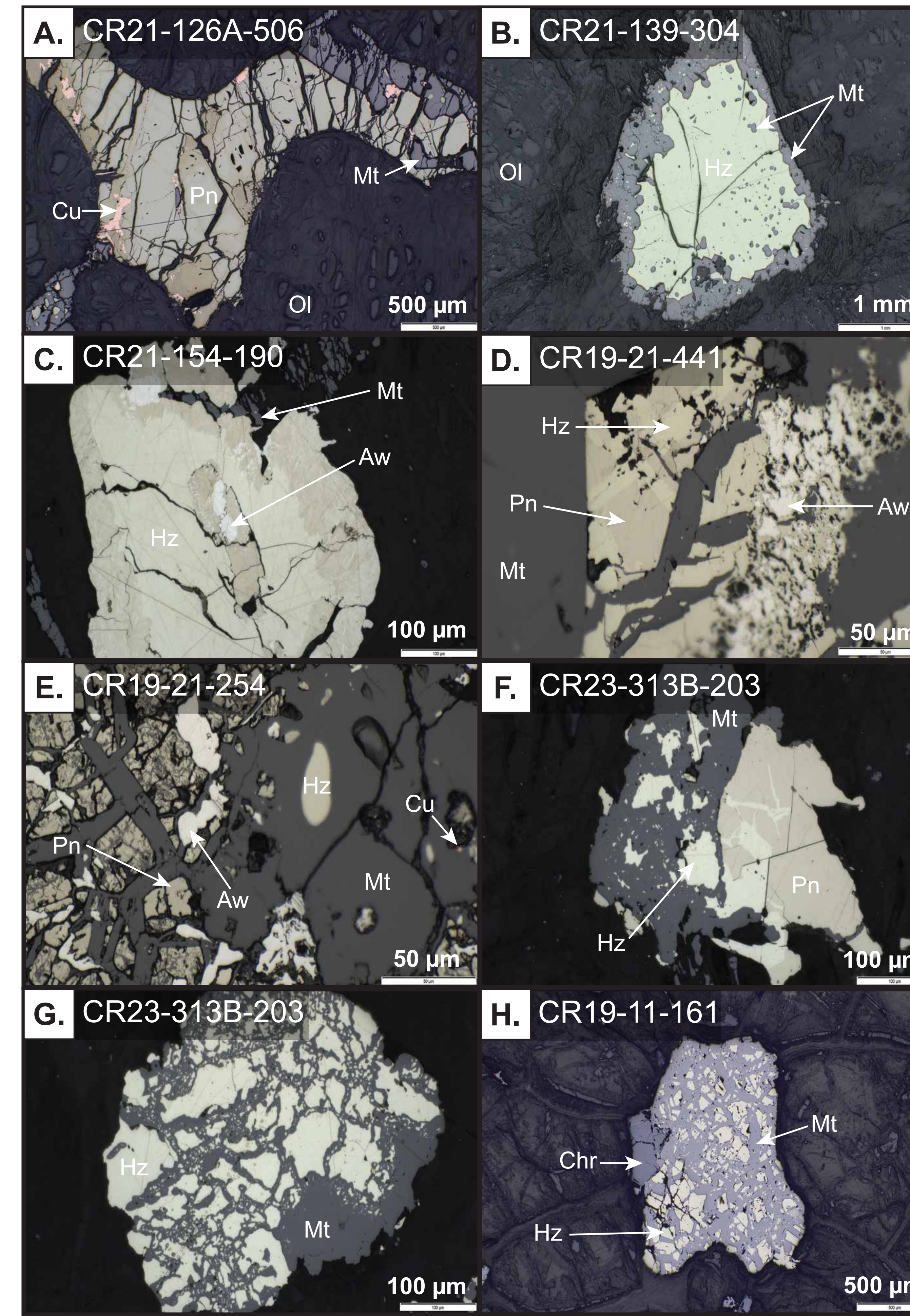


Figure 4. Reflective light photomicrographs of sulfide, oxide, and alloy assemblages in steadily increasing serpentinized dunite samples (top left to bottom right). Mineral abbreviations: Pn - pentlandite ( $Fe_{4.5}Ni_{4.3}S_8$ ), Hz - heazlewoodite ( $Ni_3S_2$ ), Aw - awaruite ( $Ni_2Fe$ ), Mt - magnetite, Cu - native copper, Chr - chromite, and Ol - olivine. A. Primary Pn grain with subtle replacement by Cu and Mt. B. Hz grain with inclusions of and enclosed by Mt. C. Hz grain coexisting with Aw. D-E. Pn grain partly replaced to Hz, Aw, and Mt. F. Partial replacement of Pn by Hz and Mt. G-H. Grains of Hz and Mt with limited preservation of Pn.

## MINERAL CHEMISTRY

Figure 5 shows the composition of olivine (Ni content vs. forsterite content) from the Crawford deposit (in colour) from samples where primary olivine could still be analyzed (regardless of the degree of serpentinization). The sample distribution is consistent with Continental Large Igneous Provinces (as summarized in Barnes et al. 2023) and other mafic-ultramafic magmas (Alexo, Betheno, Dumont, Santa Rita; see caption for references). For CR21-126A and CR21-154, the triangular symbols indicate the inferred basal part of the dunite, and the circles indicate the inferred tops (including CR21-108 circles). All other Crawford samples are from the inferred middle part of the dunite and are indicated as squares. As expected, basal sections of the dunite are more magnesian (up to Fo<sub>90</sub>) and have higher Ni content (up to 3500 ppm), consistent with them being the earlier olivine to crystallize. The lower Ni content (~2200 ppm) corresponds to less magnesian olivine (Fo<sub>86</sub>) higher in the magmatic stratigraphy.

EPMA of sulfides and alloys from 9 samples, consisting of 54 grains of pentlandite, 38 grains of heazlewoodite, and 7 grains of awaruite, yielded  $Fe_{4.5}Ni_{4.3}S_8$  for pentlandite (Fe:Ni close to 1:1),  $Ni_2Fe$  for awaruite, and stoichiometric heazlewoodite of  $Ni_3S_2$ .

The serpentinization of the average olivine composition at Crawford (close to Fo<sub>90</sub>) is best explained by the serpentinization reaction in Eckstrand (1975):

$$30(Mg_{0.9}Fe_{0.1})_2SiO_4 + 41H_2O = 15Mg_3Si_2O_5(OH)_4 + 9Mg(OH)_2 + 2Fe_3O_4 + 2H_2$$

Whereas the effect of serpentinization in pentlandite (Fe:Ni at Crawford is close to 1:1) is well explained by the reaction described in Klein & Bach (2009):

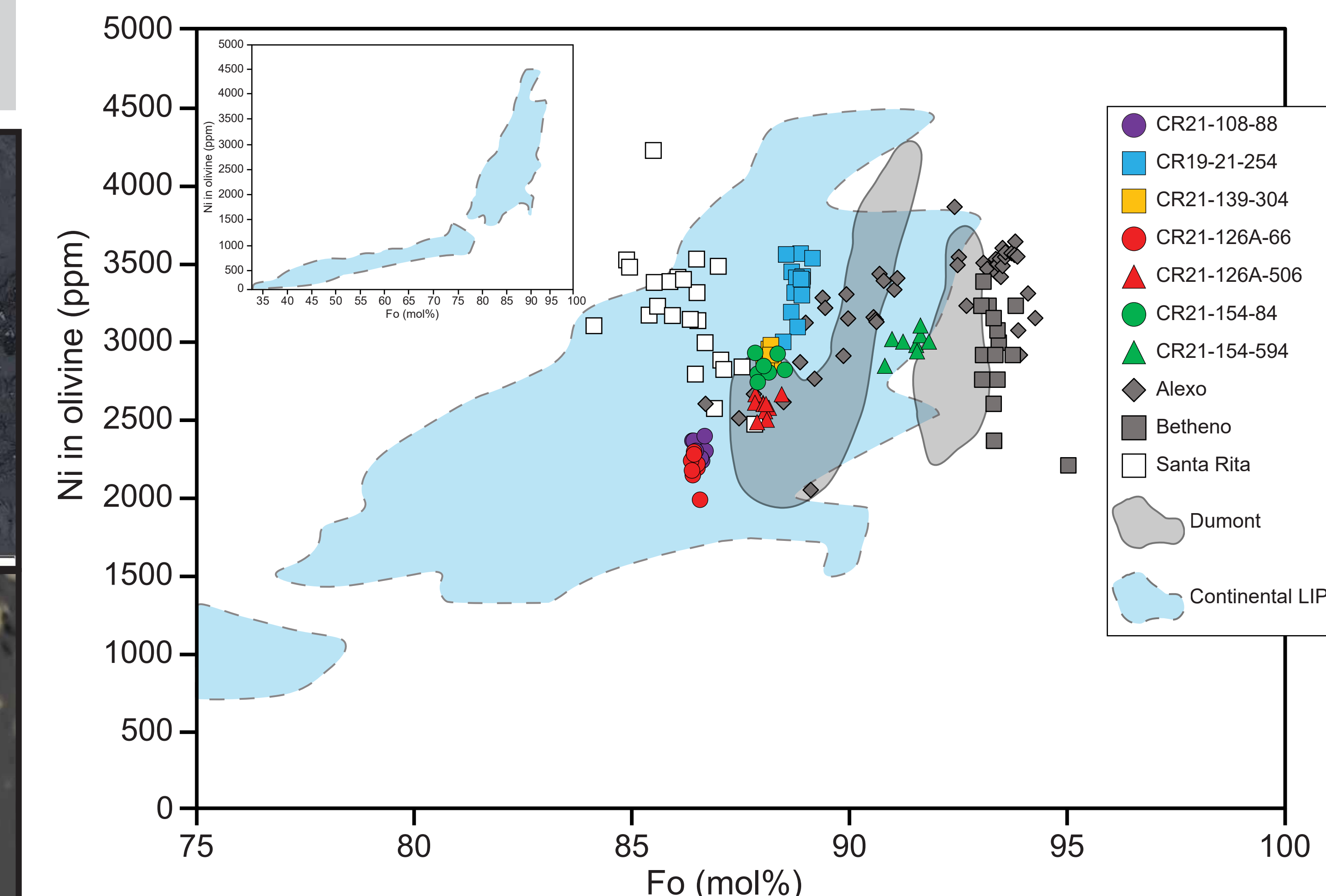
$$4Fe_{4.5}Ni_{4.5}S_8 + 20H_2O + 6H_2 = 5Fe_3O_4 + 3Ni_3Fe + 3Ni_3S_2 + 26H_2S$$


Figure 5. Measured olivine composition (Ni content against forsterite content) for Crawford samples with preserved olivine (regardless of degree of serpentinization). Other available data for context. The large blue field is the Continental Large Igneous Provinces (CLIPs) simplified from Barnes et al. (2023). Other data are from Alexo (GEOROC Database 2023), Betheno and Santa Rita (Barnes et al. 2013), and Dumont (extracted from Fig. 10 in Sciortino et al. 2015). Inset of the entire range of CLIPs for context is in the top left corner.

## CONCLUSIONS

- At Crawford, the degree of serpentinization is controlled by proximity to faults in the complex. The evidence is provided by the observed mineralogical transformations of primary Pn to Hz, Aw, and Mt with progressive serpentinization in the Main-West zone and dominant Hz and Mt with limited preservation of Pn in the completely serpentinized East zone.
- The Fo and Ni content in olivine (up to Fo<sub>90</sub> and up to 3500 ppm) are consistent with the most magnesian and Ni-rich samples from LIPs and other mafic-ultramafic magmas.
- Serpentinization of these types of intrusions simultaneously liberates Ni from olivine and increases grades (Ni:S) in sulfides via the formation of secondary sulfides (e.g., heazlewoodite) and alloys (e.g., awaruite).

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## Contact

ncarter1@laurentian.ca; pjugo@laurentian.ca

