Mineralogy of sulphide, arsenide, and platinum group minerals from the DJ/DB Zone of the Turnagain Alaskan-type ultramafic intrusion, north-central British Columbia

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Abstract
The Turnagain intrusion (ca. 190 Ma) is an Alaskan-type, ultramafic body emplaced in an orogenic setting that is host to a significant nickel-cobalt resource (865 Mt at 0.21% per tonne Ni and 0.013% per tonne Co). The 24 km^2 intrusion comprises a suite of ultramafic rocks including dunite, wehrlite, clinopyroxenite, and hornblendite with minor late-stage dioritic intrusions and inclusions of hornfelsed country rocks. Soil geochemistry and drilling led to the discovery of an area of copper and platinum group element (PGE) enrichment in a previously underexplored area of the intrusion, the DJ/DB zone, 2.5 km northwest of the nickel resource. We conducted a detailed mineralogical investigation to assess the range of compositions and textures of platinum group minerals (PGM) and associated sulphides in the DJ/DB zone. Mineralized clinopyroxenites and hornblendites, typically with less than 5 vol.% sulphide, contain mainly chalcopyrite and pyrrhotite with minor pyrite and pentlandite, and host a variety of arsenides, arsenic-antimony sulphides, and PGM. Arsenic and antimony-bearing phases are typically related to chalcopyrite and include cobaltite (CoAsS), nickeline (NiAs), gersdorffite (NiAsS), ullmannite (NiSbS) tucekite ($Ni_9Sb_2S_8$), and hauchecornite ($Ni_9Bi(Sb,Bi)S_8$). Identified PGM are predominantly sperrylite ($PtAs_2$) and sudburyite (PdSb), with minor Pd-melonite [$(Ni,Pd)Te_2$], hongshiite (PdCu), testibiopalladite [PdTe(Sb,Te)], and genkinite [$(Pt,Pd)_4Sb_3$]. Platinum- and palladium-bearing minerals commonly form equant 1 - 40 µm grains, within chalcopyrite, pyrrhotite, pentlandite, cobaltite and silicates. Sperrylite and sudburyite also occur as veinlets within and as partial rims (~ 1 - 10 µm thick) on the periphery of base metal sulphides. The textural paragenesis and mineral chemistry of PGM and associated minerals in the DJ/DB zone of the Turnagain intrusion are compared to those observed from other Alaskan-type intrusions. These findings highlight the potential for finding PGE-mineralized units in other Alaskan-type intrusions in the Canadian Cordillera and older orogenic ultramafic-mafic intrusions elsewhere in Canada.

Keywords: Platinum group elements, platinum group minerals, ultramafic intrusion, Alaskan-type, Turnagain intrusion, arsenide minerals, antimonide minerals

1. Introduction

Ultramafic-mafic intrusions host economic deposits of nickel, copper and platinum group element (PGE) in Canada (e.g. Sudbury, Ontario, Naldrett, 2011; Voisey's Bay, Labrador, Naldrett, 1999) and worldwide (e.g. Bushveld Complex, South Africa, Maier and Groves, 2011; Noril'sk, Russia, Naldrett, 1999; Stillwater Complex, USA, Maier and Groves, 2011). These intrusions occur in diverse geological settings, but are common in areas of continental rifting where high degrees of partial melting extract chalcophile elements from the mantle and crustal sulphur promotes sulphide saturation of the magma (Ripley, 2010; Naldrett, 2011). Historically, areas of subduction-related magmatism have been less favourable environments for exploration. However, recent examples of ultramafic-mafic-hosted Ni-Cu-PGE mineralization in supra-subduction-zone or "orogenic" settings include the Aguablanca mine in Spain (Piña et al., 2012), an Alaskan-type intrusion at Duke Island, southeastern Alaska (Irvine, 1974; Ripley, 2010), and the former Giant Mascot mine in southern British Columbia (Manor et al., this volume). Such orogenic settings may become a focus for future exploration for Ni-Cu-PGE mineralization in the Canadian Cordillera and elsewhere.

Alaskan-type ultramafic-mafic intrusions in the northern Cordillera have long been known (Taylor, 1967). In British Columbia, these intrusions are hosted by the accreted arc terranes of Quesnellia and Stikinia, and range in age from mid-Triassic (ca. 237 Ma at Lunar Creek) to Early Jurassic (ca. 186 Ma at Polaris; Nixon et al., 1997). Key petrologic traits include a general lack of orthopyroxene in ultramafic-mafic cumulates (Nixon and Hammack, 1991; Taylor, 1967) and ultramafic-hosted PGE mineralization, that is commonly related to chromitite layers and their derivative PGE-rich placer deposits (Johan, 2002; Macdonald, 1987; Nixon et al., 1990). Base metal sulphide mineralization is not a common characteristic of Alaskan-type complexes (Nixon et al., 1997). The Turnagain intrusion underlies an area of ~ 25 km^2, approximately 70 km east of Dease Lake (Fig. 1). It represents the only sulphide-bearing Alaskan-type intrusion currently known in British Columbia, with a significant Ni-Co resource: 865 Mt at 0.21% per tonne Ni and 0.013% per tonne Co (Riles et al., 2011).

Exploration of the Turnagain intrusion has mainly focussed on the large low-grade nickel resource in the southern part of the intrusion, the Horsetrail zone (Fig. 1). Geochemical soil surveys in 2004 and subsequent drilling revealed elevated concentrations of copper, platinum and palladium in the poorly exposed southwestern part of the intrusion, an area known as the DJ/DB zone (Figs. 1, 2). Relatively little information is available from this part of the intrusion. To rectify this, and to better document the Turnagain intrusion as an example of an orogenic deposit, herein we present initial observations of the textures and composition of the various sulphide, semimetal-rich and platinum group minerals (PGM) identified in drillcore samples from the DJ/DB zone.

2. Regional geology

The Turnagain intrusion lies in a 6 km wide assemblage of Late Paleozoic metasedimentary and metavolcanic rocks of the Yukon-Tanana terrane (Nixon, et al., 2012; Fig. 1). These host rocks are tectonically juxtaposed against Lower Paleozoic continental margin successions (Kechika and Boya formations) of ancestral North America (Cassiar terrane) to the east, and separated from Mesozoic granitic plutons of the Quesnel terrane to the west by the Kutcho Fault (Gabrielse, 1998; Nixon et al., 2012). The northern and eastern margins of the intrusion are in fault contact with pyritic graphitic phyllite and slate. Shear bands in the footwall of this steeply dipping (reverse) fault indicate an eastward direction of tectonic transport (Nixon, 1998; Fig. 1). At the southern and western margins, however, intrusive contacts with hornfelsed metasedimentary and metavolcanic rocks have been observed both in outcrop, at an inlier in the western extremity of the intrusion (Fig. 1), and in drillcore (Clark, 1975; Scheel, 2007).

3. Geology of the Turnagain intrusion

The Turnagain is a composite Alaskan-type intrusion that contains a suite of typical Alaskan rock types, including dunite, chromitite, wehrlite, clinopyroxenite and hornblendite (Clark, 1975, 1980; Scheel, 2007, Scheel et al., 2005).

We recognize three ultramafic stages or subintrusions, from oldest to youngest (Fig. 1): 1) wehrlites and clinopyroxenites; 2) dunite-wehrlite; and 3) clinopyroxenite-hornblendite. At the core of the intrusion, these ultramafic units are cut by a dioritic pluton (Fig. 1). Inclusions of intact and partially digested hornfelsed country rock are common in drillcore from mineralized areas, especially in dunite and wehrlite in the Horsetrail zone.

In the north, steeply dipping, cumulate layering in wehrlites and clinopyroxenites is cut by dunite along a sharp intrusive contact (Clark, 1975). Southward, the main dunite body passes into wehrlite, minor clinopyroxenite and rare hornblendite, which together form the dunite-wehrlite phase. The third and youngest phase of the ultramafic intrusion is the clinopyroxenite-hornblendite (± wehrlite) unit that comprises the DJ/DB zone. Although outcrops are scarce, the relative age of the clinopyroxenite-hornblendite unit can be established using large (up to ~ 2 m) boulders that contain angular blocks of dunite with serpentinized rims enclosed in a coarsely crystalline matrix of hornblendite and hornblende clinopyroxenite. Diorite and leucodiorite dikes cut hornblendite-clinopyroxenite indicating that the dioritic pluton represents the final intrusive event.

The sulphide content of the rocks of the Turnagain intrusion is highly variable. Most rock types carry small amounts of disseminated sulphide (up to 1 vol.%,). However, disseminated sulphides in the Horsetrail zone, the main Ni-Co resource, are generally more abundant (~ 5 vol.%), and locally become net-textured or semi-massive (up to 50% sulphide), and are mainly composed of Ni- and Co-rich pentlandite and pyrrhotite with minor chalcopyrite. The DJ/DB Cu-PGE-rich zone typically has Pt - Pd enrichment (maximum 4.9 ppm) spatially associated with areas of low sulphide content (< 5 vol.%), whereas localized areas of net-textured sulphides contain only background concentrations of platinum and palladium (< 10 ppb).

3.1. Geology of the DJ/DB zone

The DJ/DB zone is an elliptically shaped area (~ 3.5 km^2) at the southwestern margin of the Turnagain intrusion, approximately 2.5 km northwest of the well-mineralized Horsetrail zone. To date, 34 holes (60 - 413 m) have been drilled in the DJ/DB zone, both NQ (47.6 mm) and BQ (36.5 mm) drillcore. To establish lithological and mineralogical variations we examined eleven drillholes.

The rocks of the DJ/DB zone consist of interlayered units of clinopyroxenite and hornblendite with minor wehrlite. The mineralogy, modal abundances, and textures of these units vary significantly over short distances (< 50 cm) and contacts can be abrupt or gradational over 10s of metres (based on the predominant mineral, e.g. clinopyroxene or amphibole). Unit thicknesses measured in drillcore range from 50 cm to 155 m for clinopyroxenite, 15 cm to 57 m for hornblendite, and up to 26 m for wehrlite.

Pale grey clinopyroxenite (Fig. 3a) consists of fine- to coarse-grained (< 1 - 10 mm), randomly oriented clinopyroxene (> 60%) with interstitial magnetite (< 1 - 40%), hornblende (< 1 - 35%), biotite (< 1 - 20%), and serpentinized olivine (up to 15%). Primary biotite in clinopyroxenite is generally coarser grained (1 - 30 mm) than pyroxene and is randomly oriented to weakly aligned. Two types of magnetite are present: 1) > 1 to 10 mm blebs that are locally weakly to moderately banded (Fig. 3b); and 2) fine veinlets in serpentine-altered olivine. Clinopyroxenite is variably altered, ranging from nearly fresh to > 50% serpentine-chlorite ± biotite alteration along clinopyroxene grain boundaries. The clinopyroxenite is also cut by thin (1 - 50 mm) post-magmatic veins of coarse-grained to pegmatitic calcite and hornblende. The sulphide content of

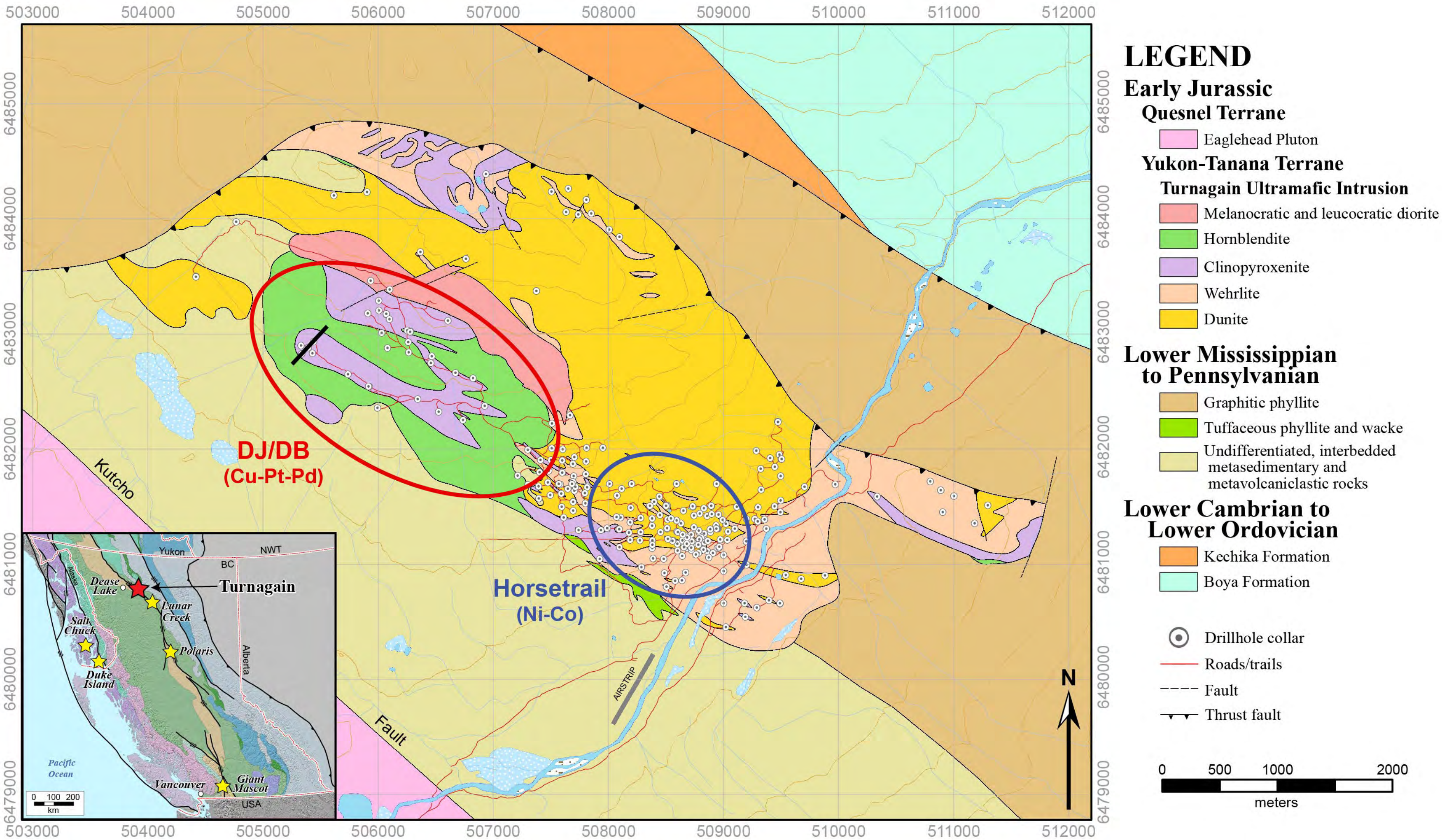

Fig. 1. Regional geological setting of the Turnagain intrusion (modified from Nixon et al., 2012) showing the DJ/DB zone (red), host to anomalous Cu-Pt-Pd concentrations and the focus of this study, and the Horsetrail zone (blue), which hosts the main Ni-Co resource. Thick black line in DJ/DB zone indicates location of cross-section in Fig. 2. Inset shows the location of the Turnagain intrusion and several other orogenic mafic-ultramafic intrusions relative to major tectonostatigraphic terranes in the northern Cordillera (modified from Colpron and Nelson, 2011). Map coordinates are in NAD 83, zone 9.

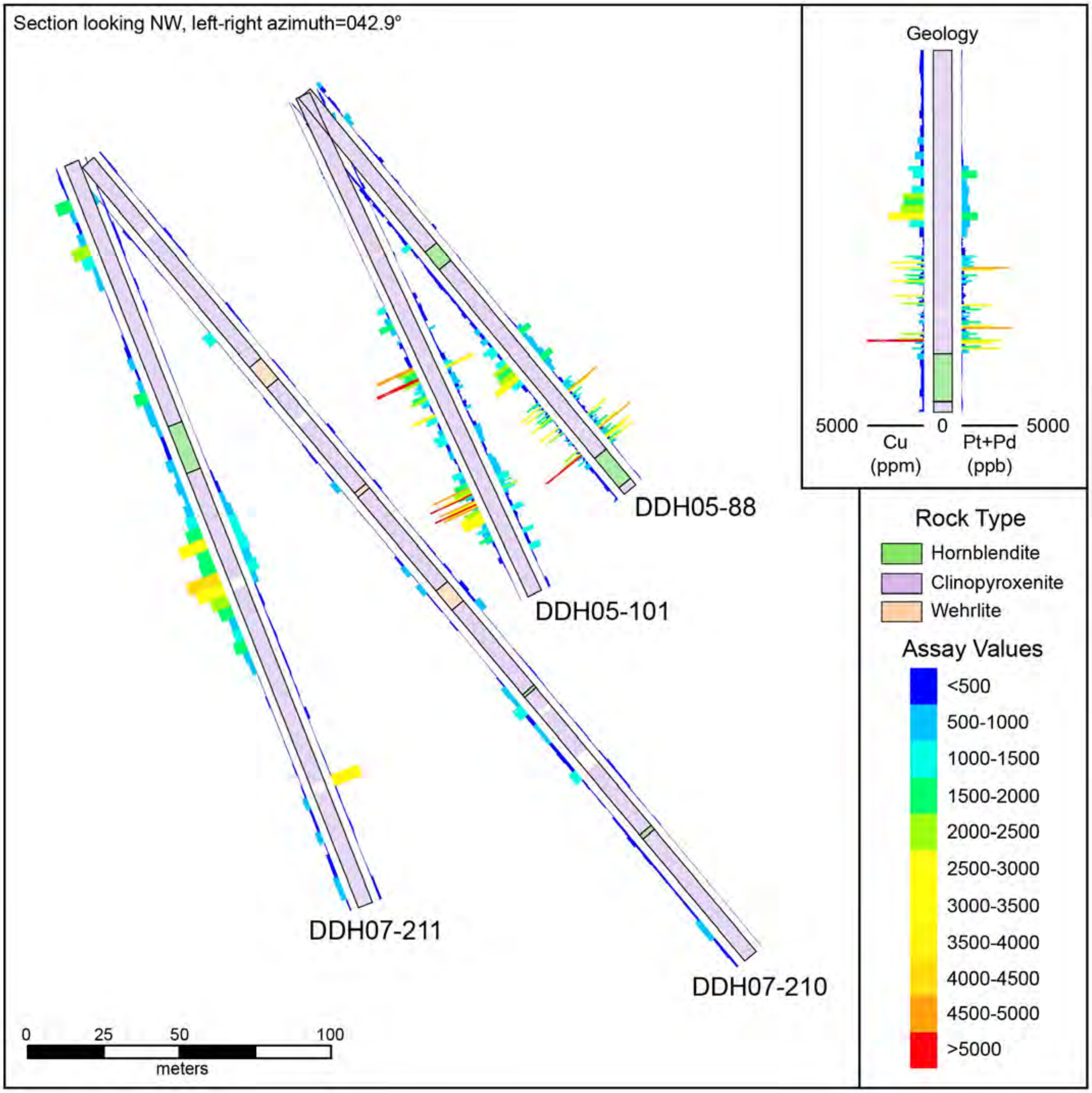

Fig. 2. Cross-section of drillhole geology and Cu, Pt and Pd concentrations through the DJ/DB zone, showing geology (centre), with Cu (left, in ppm) and PGE concentrations (right, in ppb). Maximum Cu concentration in section is 17900 ppm over 0.5 m. Maximum combined Pt+Pd concentration is 4881 ppb over 0.5 m. Note the moderate correlation between areas of high Cu and high Pt+Pd concentrations. Assay samples for all drillholes are half-core split; analytical results were obtained using 4-acid digestion ICP-ES for copper and fire assay fusion ICP-ES for Pt and Pd. Sample intervals for DDH07-210 and DDH07-211 are 4 m. Sample intervals for DDH05-88 are 2 m (3.05-105 m, 158-172.2 m EOH) and 0.5 m (105-158 m). Sample intervals for DDH05-101 are 2 m (3.7-88 m, 165-184.7 m EOH) and 1 m (88-165 m).

clinopyroxenite varies from 0 to 35% sulphide, and sulphides display disseminated, net-textured, and semi-massive textures. Areas of more intense alteration and calcite-hornblende veins also contain sulphides but these only constitute a small percentage of overall mineralization.

Dark green to black hornblendite contains fine- to coarse-grained amphibole (< 1 - 25 mm in length) with sporadic pegmatitic patches (amphibole crystal size > 45 mm). Amphiboles in the hornblendite are predominantly randomly oriented (Fig. 3c), with local zones (1 - 100 cm wide) of moderately to strongly oriented crystals (Fig. 3d). Hornblendite locally contains up to 30% clinopyroxene, with

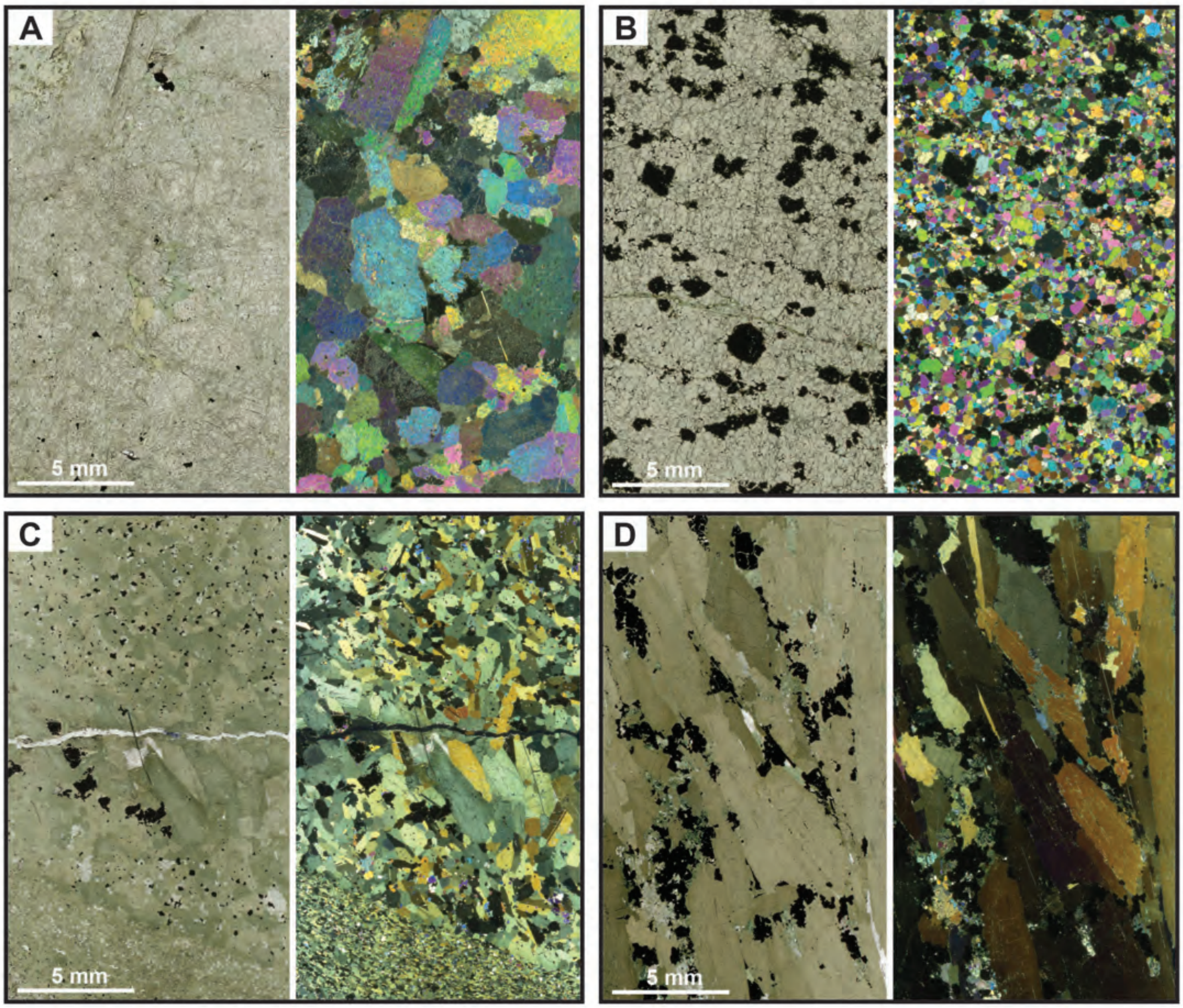

Fig. 3. Digital scans of thin sections for the major rock types from the DJ/DB zone in transmitted light (left) and cross-polarized light (right). **a)** Sample DDH05-88-1: coarse-grained clinopyroxenite with 2% sulphide and minor biotite. **b)** DDH05-89-1: fine-grained clinopyroxenite with weakly banded blebs of magnetite. **c)** DDH04-43-1: very fine-grained hornblendite in contact with fine- to medium-grained hornblendite with 5% chlorite and 3% sulphide. Coarser crystals above the contact are weakly aligned oblique to contact. **d)** DDH05-102-11: coarse-grained hornblendite with strongly oriented amphibole crystals. Sample has 5% interstitial sulphide associated with secondary chlorite.

appreciable magnetite (up to 15%) and minor biotite (up to 5%). Hornblendite contains 1 to 15% disseminated sulphide, and is mainly fresh to weakly chlorite altered. As in the clinopyroxenite, the hornblendite is cut by calcite-hornblende-sulphide veins.

Grey to pale grey, medium-grained wehrlite is typically moderately to strongly altered. Pyroxenes are largely fresh in altered wehrlite, with variable amounts of talc and chlorite along grain boundaries. Olivine typically occurs as relic grains replaced by serpentine and magnetite. The abundance of disseminated sulphide (5 - 30%) is strongly correlated to the degree of alteration, unlike those in hornblendites and clinopyroxenites.

4. Sampling and analytical methods

This study uses samples and data from surface exposures and 20 of 34 drillholes from the DJ/DB zone. Sixteen surface grab samples and 111 drillcore samples were collected during two field seasons (2011 and 2013). Surface samples were obtained from outcrop and large loose blocks close to drill sites in the DJ/DB zone. We examined core from drillholes that yielded high Cu-Pt-Pd assay values and provided even spatial distribution across the DJ/DB zone. The core was observed for variations in rock type, sulphide content and textures. Sampling was concentrated in areas with assay values greater than 500 ppb combined Pt + Pd, in addition to a suite of samples with medium (100 - 500 ppb Pt + Pd) and low (Pt + Pd > 100 ppb) concentrations, and representative lithologies from the area.

Ninety-six polished thin sections from drillcore samples were examined petrographically using plane-polarized transmitted light, cross-polarized transmitted light, and reflected light. Anomalously high Pt + Pd-bearing samples (n=14) were chosen for scanning electron microscope (SEM) analysis to identify PGM, associated sulphides, and silicates, and determine controls on the mineralization. Scanning electron microscope analyses were collected at both the Electron Microbeam/X-Ray Diffraction Facility at the University of British Columbia, Vancouver (UBC) and the SEM Facility at the Geological Survey of Canada, Ottawa (GSC). At UBC, back-scattered electron (BSE) imaging was carried out on a Philips XL-30 scanning electron microscope. An operating voltage of 15 kV was used with a spot diameter of 6 µm. At the GSC, BSE imaging was carried out on a Zeiss EVO 50 series SEM with extended pressure capability (up to 3000 Pascals), equipped with a backscattered electron detector (BSD). Results of the petrographic and SEM work obtained to date from are presented below.

5. Mineralogy

5.1. Base metal sulphides

Base metal sulphides in the DJ/DB zone of the Turnagain intrusion are mainly pyrrhotite and chalcopyrite with minor pyrite and pentlandite. Minor to trace accessory phases include millerite (NiS), sphalerite (ZnS), bornite (Cu_5FeS_4), marcasite (FeS_2), molybdenite (MoS_2), siegenite [$(Ni,Co)_3S_4$], and selenium-rich galena (PbS). Pyrrhotite is the most prevalent sulphide, commonly forming sub-millimetre to 3 mm diameter grains interstitial to silicates, with or without chalcopyrite (Fig. 4a), and locally forming net-textured layers or massive veins. Chalcopyrite is commonly intergrown with pyrrhotite, but also occupies veinlets in silicates and along silicate grain boundaries. Chalcopyrite grains may also host various arsenic- and antimony-bearing minerals (Fig. 4b). Pyrite is typically observed as aggregates of euhedral to subhedral crystals (10 - 50 µm) up to 2 mm in diameter in pyrrhotite or chalcopyrite (Figs. 4c, d). Pentlandite forms both sub-millimetre sized crystals in pyrrhotite and chalcopyrite (Fig. 4e), and exsolution flames in pyrrhotite grains (Fig. 4f).

5.2. Arsenides, sulpharsenides and sulphantimonides

Arsenides, sulpharsenides and sulphantimonides are common accessory minerals (< 1%) in the DJ/DB zone. They are only observed in clinopyroxenite and are commonly intergrown with chalcopyrite. Nickeline (NiAs) is the only true arsenide mineral present and is found exclusively as anhedral grains (2 - 30 µm) in cobaltite and gersdorffite (Fig. 5a). Sulpharsenide and sulphantimonide minerals include (in decreasing order of abundance): cobaltite (CoAsS), solid solution end-members gersdorffite (NiAsS) and ullmannite (NiSbS), tucekite ($Ni_9Sb_2S_8$), and hauchecornite ($Ni_9Bi(Sb,Bi)S_8$). Cobaltite is present in two distinct forms: 1) subhedral to anhedral grains and grain aggregates (1 - 70 µm across, Figs. 5a, 5b); and 2) single, euhedral grains (50 µm diameter, Figs. 5c, 5d). The former are only found in chalcopyrite, locally enclosing anhedral nickeline and pentlandite, whereas the latter are found enclosed by, or at the margins of, chalcopyrite or pyrrhotite blebs and in serpentine close to magnetite. Subhedral to anhedral grains of gersdorffite, up to 20 µm, are enclosed by chalcopyrite (Fig. 5e); rarely, gersdorffite encloses nickeline (Fig. 5f). The three sulphantimonide phases were only observed in one sample (DDH07-211-1), all in a single chalcopyrite bleb. Ullmannite is found as submicron to 10 µm grains, whereas tucekite is observed as 20 - 50 µm grains exhibiting 1 - 5 µm thick rims of hauchecornite (Fig. 5f).

5.3 Platinum group minerals

A variety of platinum group minerals have been identified in clinopyroxenite and hornblendite from the DJ/DB zone (Table 1). All PGM identified contain either platinum or palladium; significant concentrations of other PGE are lacking. The two main minerals observed are sperrylite ($PtAs_2$) and sudburyite [(Pd,Ni)Sb]. Minor PGM include Pd-melonite [$(Ni,Pd)Te_2$], hongshiite (PdCu), testibiopalladite [PdTe(Sb,Te)], and genkinite [$(Pt,Pd)_4Sb_3$] (Table 1). Clinopyroxenite is host to all varieties of PGM, whereas hornblendite only contains sperrylite. Sperrylite and sudburyite are present as: 1) equant grains 1 to 20 µm in diameter (Fig. 6); and 2) partial rims, 1 - 10 µm thick around sulphides (Fig. 7). Equant sperrylite and sudburyite grains are principally found in or at the margins of chalcopyrite and pyrrhotite. However, they are also in clinopyroxene and serpentine, adjacent to sulphide blebs. Sperrylite and sudburyite rims are only in clinopyroxenite, forming along the periphery of, or along fractures in, pyrrhotite and chalcopyrite. All of the minor PGM phases form equant grains, 1 to 40 µm in diameter, in chalcopyrite and pyrrhotite.

6. Discussion

The sulphide abundance and the distribution and mineralogy of platinum group minerals in the Turnagain intrusion differ from most Alaskan-type intrusions. Alaskan-type intrusions are typified by relatively low sulphur fugacities during crystallization, which results in early crystallization of Pt-Fe alloys with chromite in dunite and only minor sulphide phases (Johan, 2002). In contrast, the Turnagain intrusion is sulphide-rich (Nixon, 1998) due to significant assimilation of crustal sulphur during magma emplacement (Scheel, 2007). In addition, it is clear that the younger clinopyroxenite-hornblendite units of the DJ/DB zone and older dunite-wehrlite in the main part of the intrusion carry different metal endowments. Ni-sulphide mineralization is contained in wehrlites and dunites of the Horsetrail zone, whereas PGE mineralization in the DJ/DB zone occurs as Pt- and Pd-rich arsenides and antimonides in clinopyroxenite.

Sulphide-rich PGE mineralization is found in other orogenic intrusions in British Columbia and Alaska, including the Salt Chuck, Duke Island, and Giant Mascot intrusions. The Salt Chuck (early Paleozoic) Alaskan-type intrusion in southeastern

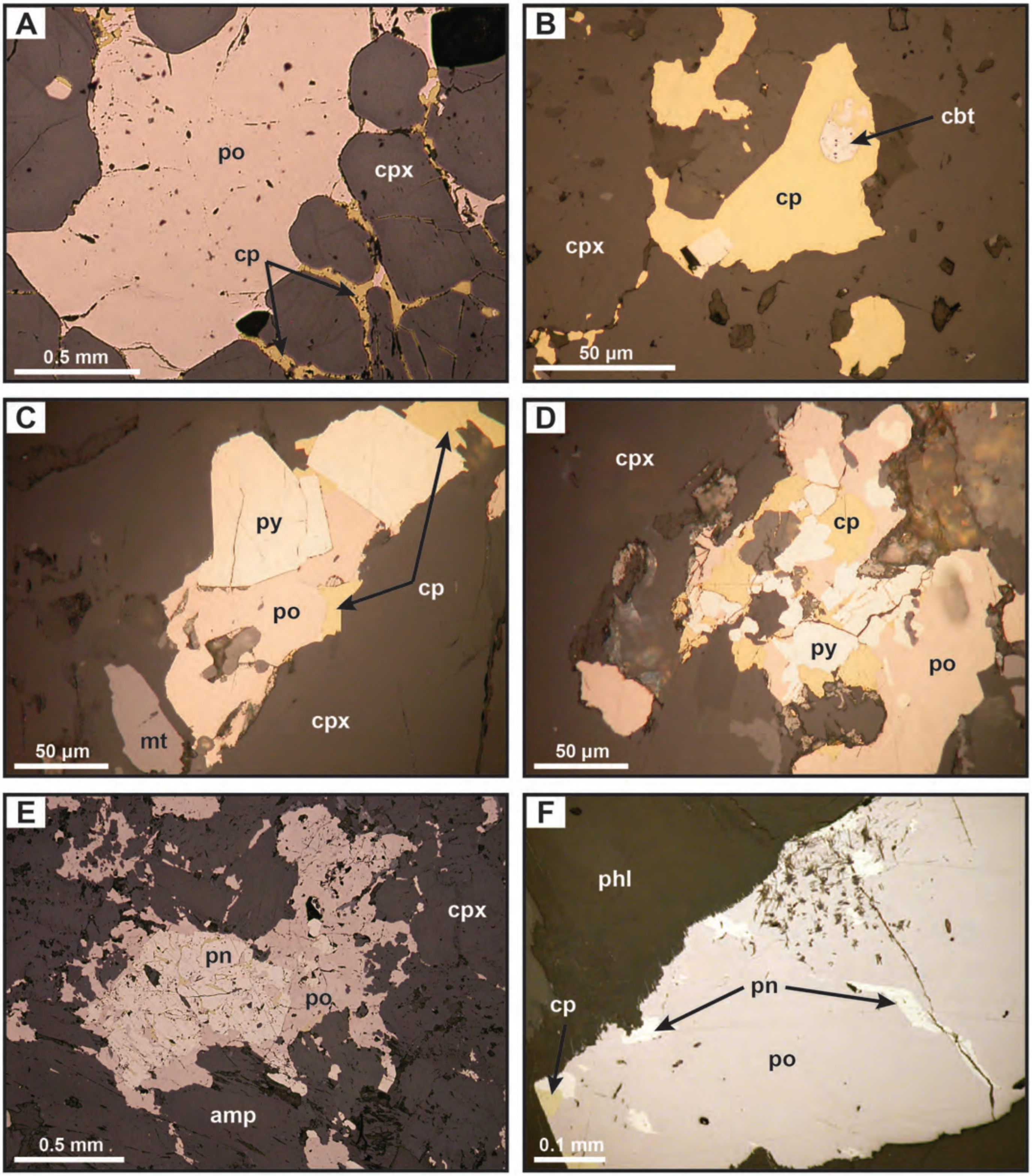

Fig. 4. Photomicrographs in reflected light of base metal sulphide minerals in clinopyroxenite from the DJ/DB zone. **a)** DDH07-211-5: coarse-grained interstitial pyrrhotite bleb with peripheral chalcopyrite along grain boundaries of surrounding clinopyroxene grains. **b)** DDH07-211-4: chalcopyrite bleb in clinopyroxenite containing a grain of subhedral cobaltite in pyroxene. **c)** DDH07-211-4: coarse-grained euhedral pyrite within a bleb of pyrrhotite and chalcopyrite. **d)** DDH07-211-4: an aggregate of subhedral pyrite in a composite bleb of pyrrhotite and chalcopyrite. **e)** DDH05-88-102: blocky pentlandite in pyrrhotite. **f)** DDH05-98-2: pentlandite exsolution lamellae (i.e., flames) in pyrrhotite. Mineral abbreviations: cpx, clinopyroxene, po, pyrrhotite; cp, chalcopyrite; cbt, cobaltite; py, pyrite; mt; magnetite; pn, pentlandite; amp, amphibole; phl, phlogopite.

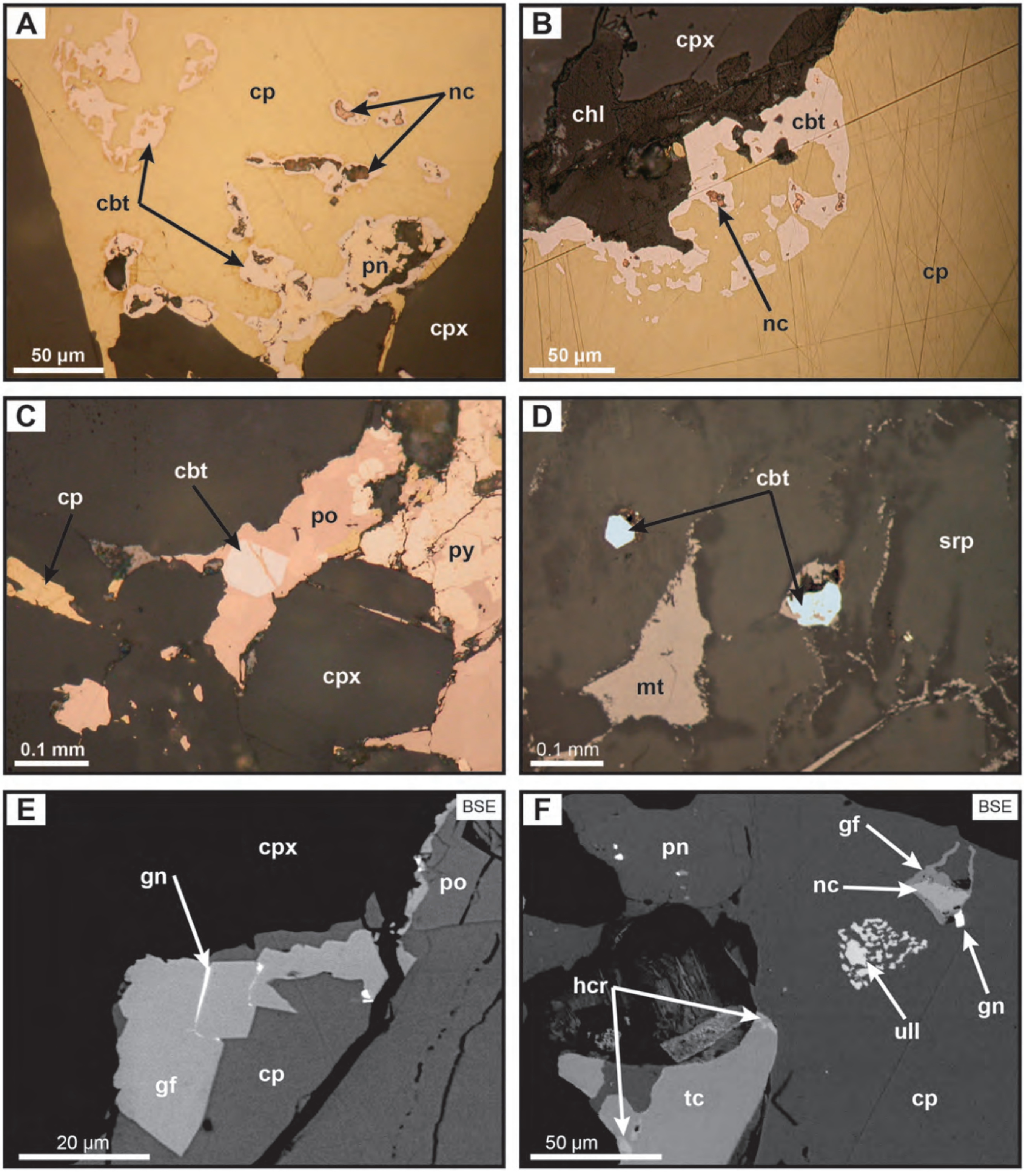

Fig. 5. Photomicrographs and electron backscatter images of arsenide, sulpharsenide and sulphantimonide minerals from the DJ/DB zone. **a)** DDH07-211-1: chalcopyrite bleb containing subhedral to anhedral cobaltite. Anhedral crystals of pentlandite and nickeline are enclosed in cobaltite. **b)** DDH07-211-1: nickeline within cobaltite at the periphery of a chalcopyrite bleb. **c)** DDH07-211-5: fractured, euhedral grain of cobaltite in pyrrhotite in clinopyroxenite. Pyrrhotite also contains pyrite and chalcopyrite. **d)** DDH05-101-1: two subhedral cobaltite crystals in serpentine near magnetite. **e)** DDH07-211-1: subhedral, cobalt-rich gersdorffite within chalcopyrite with arsenic-rich galena in fractures. **f)** DDH07-211-1: chalcopyrite bleb containing blebs of pentlandite, galena, gersdorffite, ullmannite, and tucekite. Nickeline is enclosed in gersdorffite and tucekite is partly rimmed by hauchecornite. Mineral abbreviations as in Fig. 4, except: nc, nickeline; chl, chlorite; srp, serpentine; gf, gersdorffite; gn, galena; ull, ullmannite; tc, tucekite; hcr, hauchedornite.

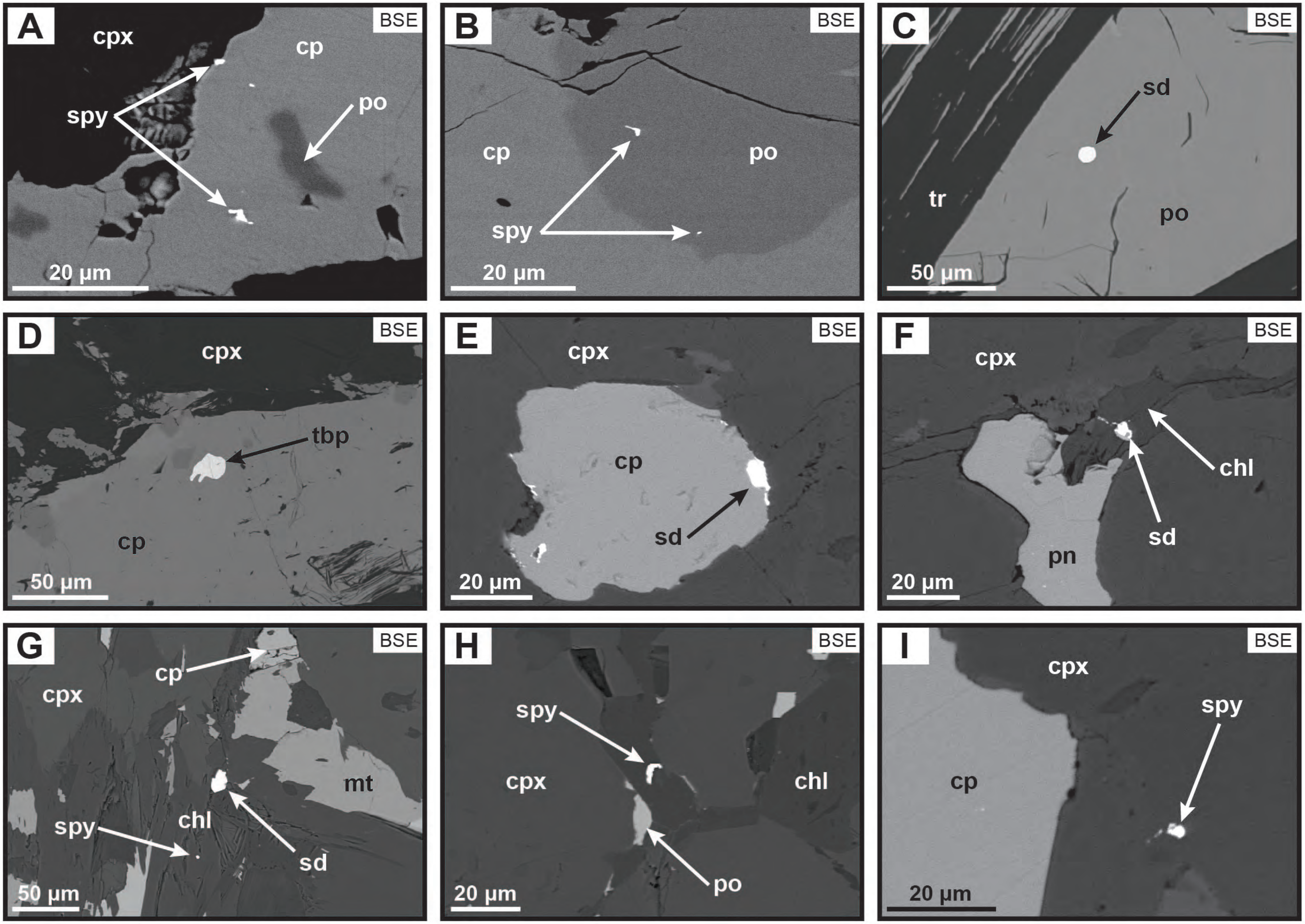

Fig. 6. Electron backscatter images of platinum group minerals from the DJ/DB zone. **a)** DDH07-211-5: sperrylite inclusions in chalcopyrite with minor pyrrhotite. **b)** DDH07-211-5: sperrylite in pyrrhotite, near a contact with chalcopyrite. **c)** DDH06-161-3: sudburyite grain enclosed in pyrrhotite. **d)** DDH06-161-3: anhedral grain of testibiopalladite in chalcopyrite. **e)** DDH05-88-1: sudburyite on the periphery of a chalcopyrite bleb in contact with clinopyroxene. **f)** DDH05-88-1: sudburyite in chlorite, adjacent to pentlandite and clinopyroxene. **g)** DDH04-59-1: sudburyite and sperrylite grains in chlorite near magnetite. **h)** DDH07-211-11: sperrylite in chlorite alteration around clinopyroxene. **i)** DDH05-88-1: satellite grain of sperrylite in clinopyroxene and adjacent to a chalcopyrite bleb. Mineral abbreviations as in Fig. 5, except: spy, sperrylite; sd, sudburyite; tr, tremolite; tbp, testibiopalladite.

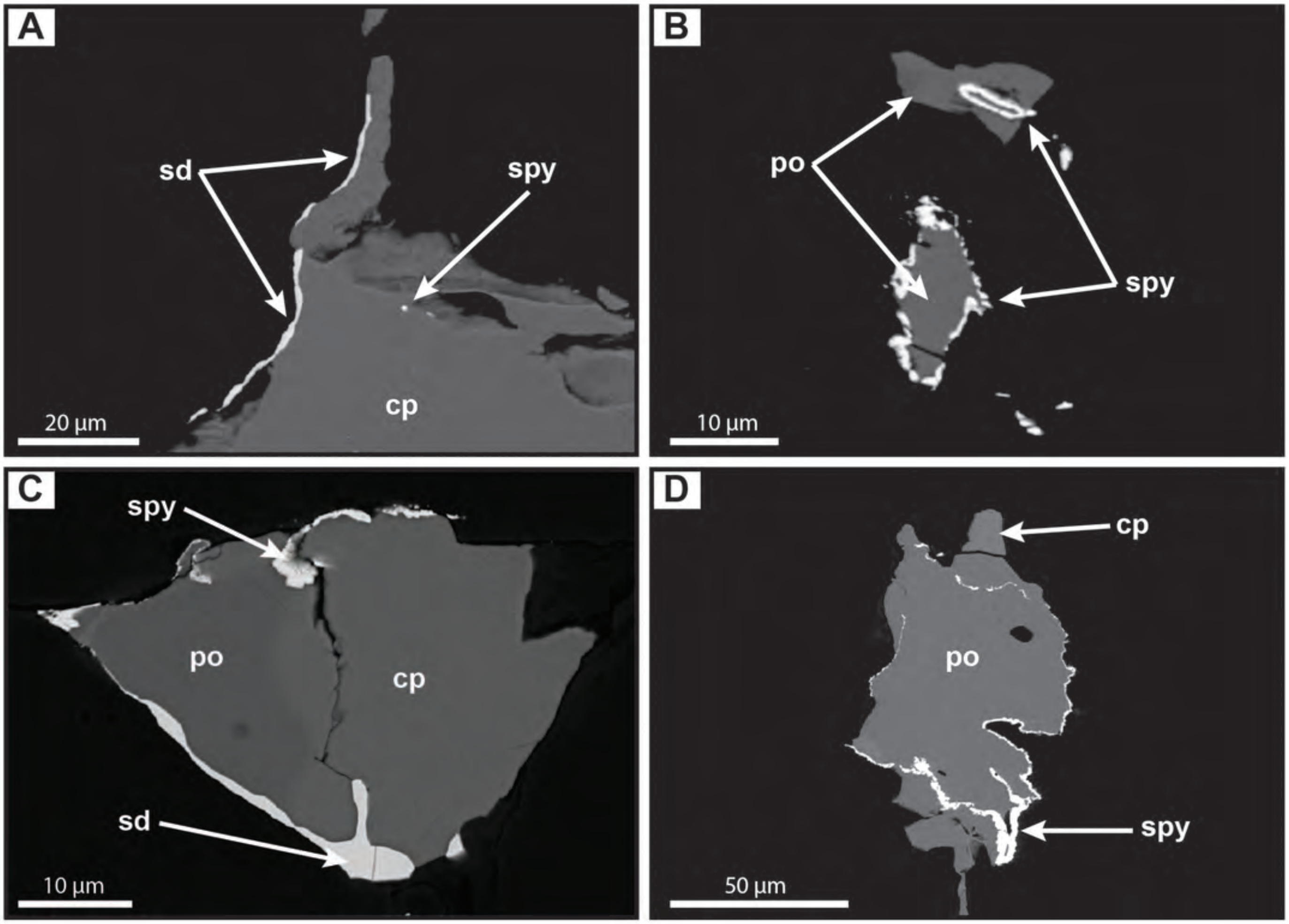

Fig. 7. Backscatter electron images of platinum group minerals forming rims around sulphides in the DJ/DB zone. **a)** DDH05-88-1: sudburyite along the periphery of a chalcopyrite grain enclosing a small grain of sperrylite. **b)** DDH05-88-1: rims and inclusions of sperrylite in pyrrhotite blebs. **c)** DDH05-102-5: sperrylite and sudburyite rims and fracture-controlled veinlets along a composite grain of chalcopyrite and pyrrhotite. **d)** DDH05-88-1: pyrrhotite bleb with a partial rim and veinlets of sperrylite. Mineral abbreviations as in Fig. 6.

Table 1. Platinum group minerals and host lithologies in the DJ/DB zone of the Turnagain intrusion (listed in decreasing order of relative abundance).

Mineral	Ideal Formula	Rock Type	Silicate/Oxide	Sulfide/Arsenide
Sperrylite (18)	$PtAs_2$	Cpxite, Hblite	cpx, chl, mt	po, cpy, cbt
Sudburyite (12)	(Pd,Ni)Sb	Cpxite	cpx, chl	po, cpy
Pd-melonite (4)	$(Ni,Pd)Te_2$	Cpxite	mt	po
Testibiopalladite (3)	PdTe(Sb,Te)	Cpxite		po, cpy
Genkinite (2)	$(Pt,Pd)_4Sb_3$	Cpxite		po
Hongshiite (1)	PtCu	Cpxite		cpy

Abbreviations: Cpxite, clinopyroxenite; Hblite, hornblendite; cpx, clinopyroxene; chl, chlorite; mt, magnetite; po, pyrrhotite; cpy, chalcopyrite; cbt, cobaltite.
Number of observed grains in brackets ( ).

Alaska (Fig. 1, inset) is an elongate body (12 km^2) that is host to significant Cu-Pd mineralization. It was mined for copper and palladium from 1916 to 1941, with average grades of 0.9% Cu, 1.4 g/t Pd, 0.57 g/t Au, and 2.8 g/t Ag, and had a total production of 2.81 million kg of Cu and 9,000 kg of Pd (Gault, 1943). The Salt Chuck intrusion is enriched in Cu and Pd (Loney and Himmelberg, 1992). However, average Cu-Pd concentrations are much higher (~ 7000 ppm Cu, ~ 1230 ppb Pd; Loney and Himmelberg, 1992) than those observed in the DJ/DB zone thus far (~ 2200 ppm Cu, ~ 174 ppb Pd; S. Jackson-Brown, unpublished data), and unlike the Turnagain intrusion, the mineralized rocks of the Salt Chuck intrusion also contain significant Au and Ag. Mineralization in the Salt Chuck intrusion, like the DJ/DB zone, is hosted by magnetite clinopyroxenite, but comprises predominantly Cu-rich sulphides (e.g., bornite, chalcopyrite) and Pd-tellurides (primarily kotulskite, PdTe; Watkinson and Melling, 1992). Metal enrichment in the Salt Chuck intrusion may record the replacement of magmatic sulphides by a Cu-rich and precious metal-rich assemblage due to the post-crystallization influx of a Cl-bearing hydrothermal fluid (Watkinson and Melling, 1992).

The Duke Island Complex, also in southeastern Alaska (Fig. 1, inset), is an Early Cretaceous Alaskan-type intrusion that has recently been found to host appreciable Ni-Cu sulphide mineralization (Ripley et al., 2005). It is an unzoned intrusion consisting of dunite, wehrlite, olivine clinopyroxenite and hornblende-magnetite clinopyroxenite (Irvine, 1974). Disseminated, and locally net-textured to massive, pyrrhotite, chalcopyrite, and pentlandite are hosted mainly in wehrlite and olivine clinopyroxenite (Thakurta et al., 2008). Elevated PGE concentrations have been reported in the Duke Island intrusion, although the mineralogy of the PGM is presently unknown. The abundance of massive sulphides in more olivine-rich rocks is similar to mineralization at the Ni-Co-mineralized Horsetrail zone of the Turnagain intrusion. PGE grades at Duke Island do not correlate with sulphide content (Freeman, 2006), similar to the DJ/DB zone (S. Jackson-Brown, unpublished data).

Mineralization in the DJ/DB zone of the Turnagain intrusion differs significantly from that of the Giant Mascot ultramafic-mafic intrusion in southern British Columbia (Fig. 1, inset), host to the province's only past-producing Ni-Cu-Co mine. The Giant Mascot deposit contains orthopyroxene-rich rock types, predominantly pyroxenite, peridotite, and minor dunite (Manor et al., this volume). Sulphide minerals include mainly pyrrhotite, pentlandite, chalcopyrite and minor pyrite, with significant PGM. Platinum and palladium commonly form bismuthotelluride and bismuthide minerals (Manor et al., this volume), distinct from the arsenic- and antimony-rich PGM identified in the Turnagain intrusion.

The Canadian Cordillera contains abundant mineral wealth, but remains underexplored for ultramafic-mafic Ni-Cu-PGE potential. This project, and others facilitated by the TGI-4 program, including work on the Giant Mascot intrusion, has confirmed that orogenic mafic-ultramafic intrusions can host significant concentrations of base and precious metals. Understanding the source(s) of, and controls on, mineralization, including mechanisms of emplacement, help derive mineralogical and geochemical methods to find similar deposits in older orogenic belts in Canada and globally.

7. Conclusions and future work

This manuscript characterizes the Cu-PGE mineralization in the DJ/DB zone of the Turnagain Alaskan-type intrusion in north-central British Columbia. The DJ/DB zone is host to a diverse population of sulphide, arsenide, sulpharsenide, sulphantimonide, and platinum group minerals that are hosted principally in clinopyroxenites and hornblendites. Field and petrographic evidence show that the clinopyroxenite-hornblendite units of the DJ/DB zone constitute a separate, later Cu-Pt-Pd-bearing intrusive phase that underwent a separate crystallization history from the earlier, Ni-Co endowed, main dunite-wehrlite units.

Investigation into the composition of the PGM and base metal sulphides in the DJ/DB zone of the Turnagain intrusion is ongoing and includes: 1) in-situ laser ablation ICP-MS analyses on PGM-bearing and non-PGM-bearing samples to determine the concentration of PGE within base metal sulphides in different textural settings; 2) whole rock PGE analyses to determine the relative metal enrichment and depletion characteristics of the late Cu-PGE enrichment in comparison to the Turnagain Ni-Co resource and other mineralization in Alaskan-type intrusions, 3) identifying hydrothermal versus orthomagmatic sources for mineralization; and 4) sulphur isotope analysis of sulphides from representative rocks types in the DJ/DB zone to evaluate the crustal sulphur source for Cu-PGE mineralization. New geoscience work on the late-stage Cu-PGE endowment of the Turnagain intrusion increases our knowledge about orogenic PGE mineralization in Alaskan-type intrusions, a style that is less common than the typical PGE-chromitite association.

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