Platinum-Group Element and Gold Deportment in the Kwanika Copper-Gold±Molybdenum Porphyry System, North-Central British Columbia (Parts of NTS 093N/06, 11)

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Introduction

The demand for critical minerals essential for clean energy technologies like wind turbines, solar panels, electric vehicles and battery storage is increasing due to the climate emergency, and the global aim for decarbonization by 2050 (Dallas et al., 2021). In Canada, platinum-group elements (PGEs), listed as critical minerals, play a crucial role in supporting clean-energy technologies, advancing a net-zero future, and in manufacturing aircraft turbines, industrial catalysts and electronics (Bossi, 2012; Natural Resources Canada, 2022). Primary economic PGE mineralization is presently extracted from stratiform chromitite reefs located within ultramafic–mafic intrusions formed between the late Archean and early Proterozoic (Maier, 2005). However, PGEs, primarily palladium, are also recovered as by-products from porphyry copper deposits (John and Taylor, 2016), such as at the Bingham Canyon mine, in the United States (Krahulec, 2018), and Kal'makyr mine, in Uzbekistan (Pas va et al., 2010).

In this paper, the deportment of PGEs and gold in the Kwanika copper-gold±molybdenum porphyry deposit in British Columbia (BC) was investigated, with a particular focus on the potential of palladium to add value as a by-product through metallurgical processes. The Kwanika porphyry deposit, located in the central Canadian Cordillera, is a Late Triassic to Early Jurassic calcalkaline system comprising the Central Zone (copper-gold-silver) and the South Zone (copper-gold-silver-molybdenum). Palladium mineralization was first identified by NorthWest Copper Corp. in 2022 but the formation mechanisms and deportment characteristics of palladium and gold remain poorly understood. The aims of this study are to determine the primary host mineral(s) for palladium and gold, identify associated mineralogy affecting metallurgical deportment, and investigate geological factors controlling palladium and gold precipitation in the deposit.

Background Information

Platinum-Group Elements (PGEs)

Platinum-group elements, which are referred to as platinum-group metals in engineering and metallurgy, are a group of six metallic elements: platinum, palladium, rhodium, ruthenium, iridium and osmium (Gunn, 2014). The PGEs rarely occur in nature as native metals but typically form alloys with each other or other metals like iron, tin, copper, lead, mercury and silver. The PGEs can also bind with metalloids (such as antimony, arsenic, bismuth and tellurium) and nonmetals (such as selenium and sulphur). They also exist in solid solutions within base-metal sulphides, where PGEs substitute for other metals within the crystal lattice without altering the mineral structure (Zientek et al., 2017). Minerals containing one or more PGE are called platinum-group minerals, with over one hundred recognized types (Cabri, 2002; Gunn, 2014). Platinum-group minerals in rocks are typically very fine grained, varying in size from submicron to hundreds of microns in diameter (Zientek et al., 2017).

PGEs in Porphyry Deposits

Porphyry copper deposits around the Pacific rim, the Mediterranean and Carpathian regions of Europe, and the Al-

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pine-Himalayan mountain system may contain PGEs as by-products, with some economic advantage for the primary producer (Eliopoulos et al., 2014; John and Taylor, 2016). Elevated concentrations of combined PGEs (>5 ppm palladium+platinum) have been identified in high-grade bornite-chalcopyrite ores and/or flotation concentrates from several alkaline porphyry deposits in various regions worldwide (Economou-Eliopoulos, 2005). Platinum-group element deportment is crucial for the recovery of PGEs as a byproduct, as it facilitates the design of the most appropriate flowsheet (Sahu et al., 2021). In BC, Thompson et al. (2002) reported elevated palladium and platinum contents at five alkaline porphyry deposits formed in island-arc tectonic settings: Galore Creek, Lorraine, Mount Milligan, Mount Polley and Ajax East. The heavy mineral concentrates they studied comprise a mixture of sulphides (bornite, chalcopyrite and pyrite) and oxides (magnetite and hematite). The PGE mineralization, especially palladium and platinum, in copper-gold porphyry deposits in the BC Cordillera is linked to postsubduction, alkali-enriched magmatism in the upper crust, with hydrothermal processes enriching palladium, gold, copper and tellurium from porphyry igneous rocks into hydrothermal deposits (Holwell et al., 2019).

Geological Setting

The Kwanika porphyry deposit is hosted in the Hogem batholith at the western margin of the Quesnel terrane. The Quesnel terrane consists of Late Triassic to Early Jurassic volcanic, sedimentary and plutonic rocks (Nicola and Takla groups) and hosts numerous porphyry copper±gold±molybdenum±silver deposits (Logan and Mihalynuk, 2014). The Hogem batholith is a composite plutonic body that contains calcalkalic and alkalic suites, as well as Alaskan-type ultramafic–mafic intrusions, and hosts several copper-gold porphyry deposits (Osatenko et al., 2020). In the project area, Late Triassic volcanic and sedimentary rocks of the Takla Group are cut by several suites of Late Triassic, Early Jurassic and Middle Jurassic plutons of the Hogem suite (Garnett, 1978; Woodsworth et al., 1991). Mineralization within the Kwanika property is associated with an Early Jurassic quartz monzonite phase of the Hogem batholith (Osatenko et al., 2020). The Central Zone (copper-gold-silver) hosts mineralization within diorite and monzodiorite porphyritic intrusions, whereas the South Zone (copper-gold-silver-molybdenum) exhibits structurally controlled mineralization in equigranular quartz monzonite to quartz monzodiorite and breccia bodies (Ausenco Engineering Canada Inc., 2023). A more detailed geological setting is provided in Osatenko et al. (2020); Figure 1 illustrates the local geology and the spatial relationships between these zones.

The Central Zone (Figure 1) comprises Takla Group andesites and Early Jurassic Hogem batholith intrusions, both cut by quartz monzonite porphyry hosting the highest grade copper-gold mineralization. Hydrothermal alteration includes an inner potassic core, an outer potassic shell that transitions into a peripheral propylitic zone and a patchy sericite alteration covering other alteration types (Osatenko et al., 2020). Palladium concentrations from fire assay analyses done on core samples 2 m long range from 0.5 to 1655 ppb (average: 17.65 ppb), with fire-assay subsample concentrations of up to 5280 ppb. Gold concentrations range from 0.5 to 12 700 ppb (average: 281 ppb), reaching up to 3180 ppb in fire-assay subsamples. Figure 2 shows a representative sample from the Central Zone used in the analysis.

In the South Zone (Figure 1), mineralization is hosted mainly in an equigranular quartz monzonite intrusion of the Hogem batholith, showing potassic, minor propylitic and sericite alteration. The mineralization in the South Zone is younger than that in the Central Zone (Osatenko et al., 2020). Based on fire assay analyses done on core samples 2 m long, palladium concentrations range from 0.5 to 73 ppb, with an average of 4.60 ppb. Gold concentrations range from 0.5 to 856 ppb, with an average of 32 ppb. Figure 3 shows a representative sample from the South Zone used in the analysis.

Ultramafic rocks, mainly hornblende pyroxenite (Figure 4), have been drilled in various locations across the Kwanika property, including north-northwest of the Central Zone (Figure 1), west of the West fault, and east of the South Zone (NorthWest Copper Corp., 2022; Lang, 2023). These ultramafic rocks of unknown age show weak alteration with chlorite, epidote and hematite after magnetite but lack copper-gold or molybdenum mineralization (Lang, 2023). Within the ultramafic rocks, palladium concentrations range from 0.5 to 410 ppb (average of 37.47 ppb), whereas gold concentrations determined from fire assay analyses done on core samples 2 m long range from 0.5 to 108 ppb (average of 4.5 ppb).

Methodology

In this study, palladium and gold deportment in three distinct geological zones were examined using mineralogical characterization (optical petrography, micro X-ray fluorescence [μ-XRF], scanning electron microscope [SEM], electron probe microanalysis [EPMA]), geochemistry and heavy mineral separation methods. Heavy mineral separation was conducted with bench-top tests performed at the Coal and Mineral Processing Laboratory of The University of British Columbia to determine mineralogy, grain size and deportment of palladium- and gold-bearing minerals, producing copper, pyrite and magnetic concentrates. All concentrates and head assay samples were analyzed using aqua-regia partial digestion followed by inductively coupled plasma–mass spectrometry (ICP-MS), fire assay fol-

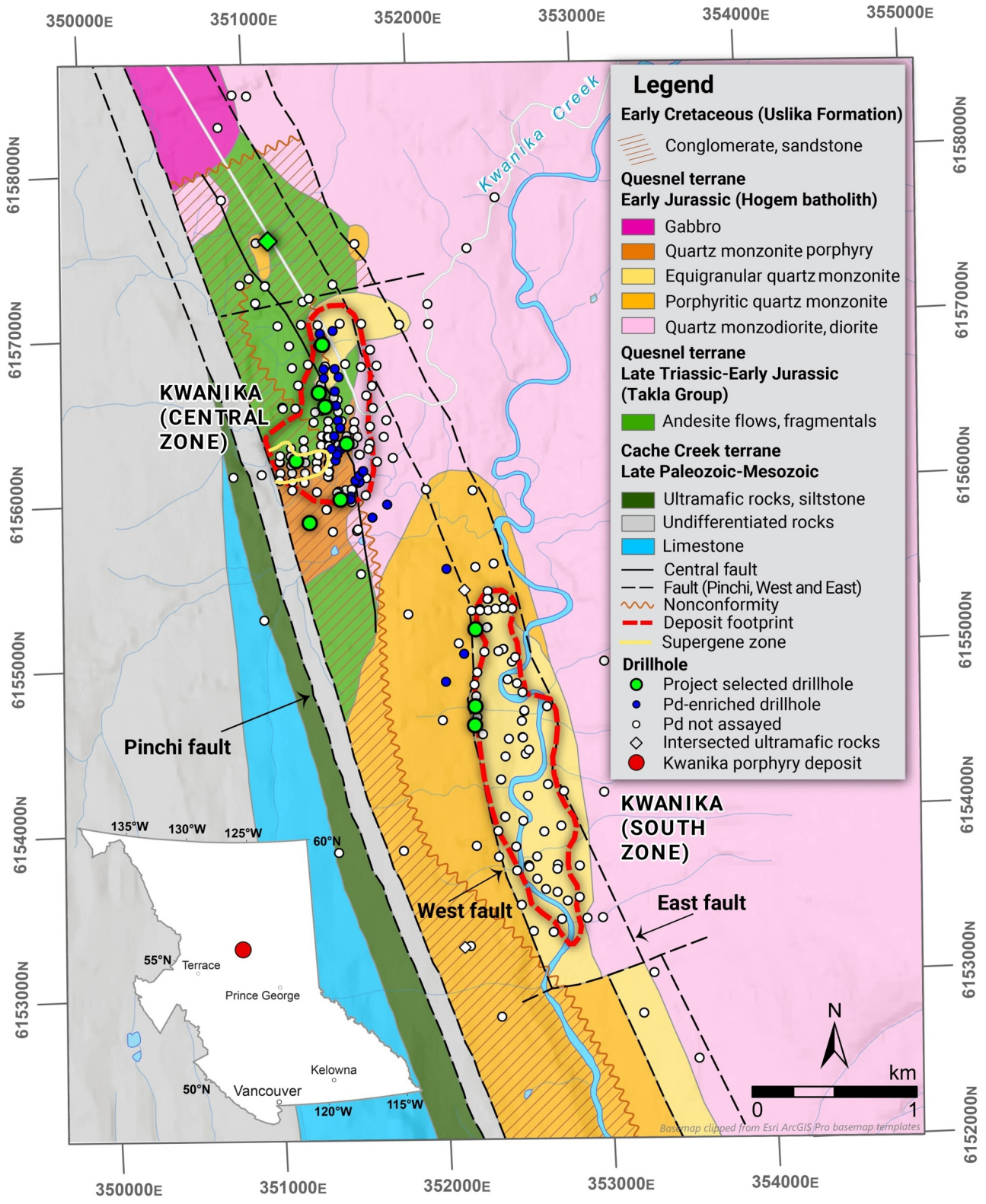

Figure 1. Geology of the Kwanika porphyry deposit area (location shown by red dot on inset map; modified from Osatenko et al., 2020). Due to overburden, the geology is projected to the surface based on drillcore data. Green circles represent drillholes selected for this study, blue circles indicate drillholes with palladium concentrations determined from fire assay analyses done on core samples 2 m long and white circles show drillholes where no analysis was conducted for palladium. Figure from Porphyry Deposits on the Northwestern Cordillera of North America: A 25 Year Update, page 489. Reprinted and revised with permission of the Canadian Institute of Mining, Metallurgy and Petroleum. Base map was created using ArcGIS® software by Esri. ArcGIS® is the intellectual property of Esri and is used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit <https://esri.ca/>. All co-ordinates are in UTM Zone 10N, NAD83.

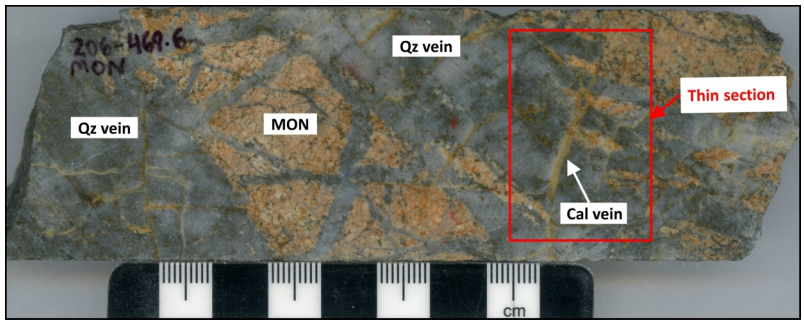

Figure 2. Representative half-core sample of monzonite cut by quartz veins from the interval with the highest palladium concentration (1655 ppb), based on fire assay analyses done on core samples 2 m long, from the Central Zone of the Kwanika porphyry deposit. The red outline indicates the sampling location of a thin section collected for scanning electron microscope analysis. Abbreviations: Cal, calcite; MON, monzonite; Qz, quartz.

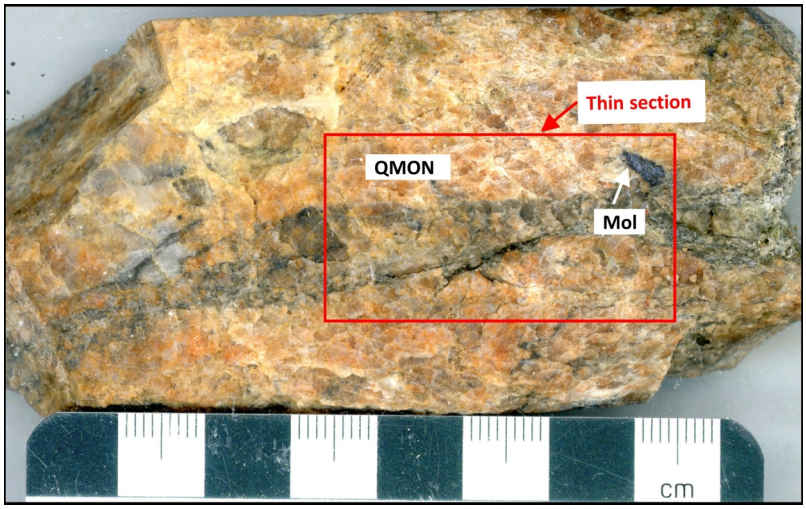

Figure 3. Representative half-core sample of quartz monzonite cut by molybdenite-quartz vein from the interval with the highest palladium concentration (73 ppb), based on fire assay analyses done on core samples 2 m long, in the South Zone of the Kwanika porphyry deposit. The red outline indicates the sampling location of a thin section collected for scanning electron microscope analysis. Abbreviations: Mol, molybdenite; QMON, quartz monzonite.

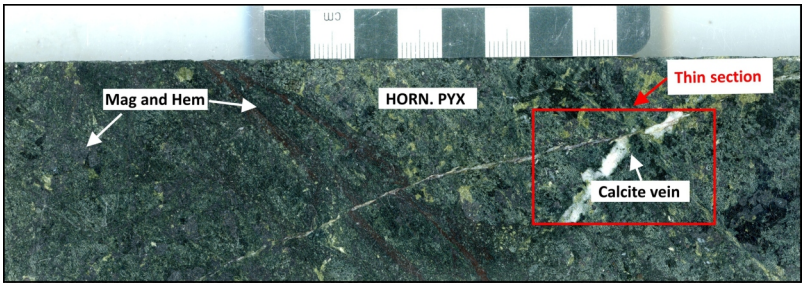

Figure 4. Representative half-core sample of hornblende pyroxenite ultramafic rock, with magnetite and hematite veins from the interval with the highest palladium concentration (410 ppb), based on fire assay analyses done on core samples 2 m long, from the Kwanika porphyry deposit. The red outline indicates the sampling location of a thin section collected for scanning electron microscope analysis. Abbreviations: Hem, hematite; HORN. PYX, hornblende pyroxenite; Mag, magnetite.

lowed by inductively coupled plasma–optical emission spectrometry (ICP-OES), and four-acid near-total digestion followed by ICP-OES+ICP-MS. Additional reporting on heavy mineral separation methods is ongoing.

For petrographic and SEM analysis, grain mounts (<106 µm) were prepared using the copper concentrate (792 ppb palladium and 13 000 ppb gold) from the Central Zone, copper concentrate (1520 ppb palladium and 396 ppb gold) from the South Zone, and high-intensity magnetic concentrate (360 ppb palladium, 52 ppb platinum and 9 ppb gold) and tailings of the ultramafic rocks (357 ppb palladium, 85 ppb platinum and 15 ppb gold) due to their elevated palladium and platinum concentrations. Thin sections were taken from core samples with elevated palladium and gold concentrations based on fire assay analyses done on core samples 2 m long. Thin sections from the Central and South zones were prepared from half-core samples exhibiting sulphide mineralization and quartz veins, whereas in the ultramafic rocks, the presence of magnetite or hematite was also a factor considered for sample collection. The SEM analysis was performed on four grain mounts and four thin sections, the locations of three of which are shown on Figures 2–4, where possible palladium and gold minerals had been observed during microscopic examinations. The SEM imaging was conducted in the Electron Microbeam and X-ray Diffraction Facility of The University of British Columbia using a SU3900 scanning electron microscope fitted with Advanced Mineral Identification and Characterization System software, both developed by Hitachi High-Tech Canada, Inc. A bright-phase search method was used to identify platinum-group minerals and gold-bearing minerals, with thin sections and grain mounts analyzed at different resolutions (0.72, 0.63 and 0.58 micron/pixel). Furthermore, the major-element composition of a complex platinum-palladium grain identified through SEM analysis in the grain mount of tailings from the ultramafic rocks was determined using a JEOL JXA-iHP200F field emission electron probe microanalyzer with Bruker 30 mm² dual silicon drift detector-energy dispersive spectrometry. Table 1 lists plati-

num-group minerals and gold-silver minerals identified through SEM analysis, corresponding to the details of the platinum-group minerals displayed in Figures 5–7.

Results

In the Central Zone, minerals containing palladium are found both enclosed in quartz, chalcopyrite and pyrite, and at the boundaries between these minerals. The size of palladium minerals in the Central Zone ranges from 0.8 to 341.1 μm^2. Minerals containing gold and silver were primarily within or at the boundaries of chalcopyrite, pyrite and bornite, and less commonly found within quartz. The gold-silver minerals in the Central Zone range in size from 0.4 to 70.0 μm^2. Gold-silver minerals with over 75% gold are classified as native gold (Alguacil, 2006), whereas some selenium-bearing types are identified as fischesserite (Bindi and Cipriani, 2004). Gold and silver tellurides were also detected but did not match known mineral compositions. Backscattered electron (BSE) images of these minerals are shown in Figure 5a–f.

In the South zone, a grain of merenskyite 0.7 μm^2 in size was identified at the quartz-chalcopyrite boundary (Figure 6a), and an unknown mineral containing silver and palladium of 1.2 μm^2 was found enclosed in biotite (Figure 6b). The elemental composition of the silver-palladium mineral does not match any known silver-bearing palla-

Table 1. Platinum-group minerals and gold-silver minerals identified in the Kwanika porphyry deposit using scanning electron microscopy. Sperrylite and isomertieite in the ultramafic rocks share an unclear boundary; the area (32.6 μm²) represents their total combined area.

Area	Hole number	Sample depth (m down hole)	MDRU Lab ID	Area (μm^2)	Host mineral	Host type	Mineral name	Figure label
Central Zone	K-21-206	469.6	BPKW0031BT	341.1	Ccp-Qz	On boundary	Merenskyite ($PdTe_2$)	5a
Central Zone	K-21-211	36.7	BPKW0033BT	232	Qz	Enclosed	Kotulskite (PdTe)	5b
Central Zone	K-21-206	469.6	BPKW0031BT	4.7	Ccp-Qz	On boundary	Isomertieite ($Pd_{11}Sb_2As_2$)	5c
Central Zone	K-21-211	36.7	BPKW0033BT	7.6	Ccp	On boundary	Fischesserite (Ag_3AuSe_2)	5d
Central Zone	K-21-211	36.7	BPKW0033BT	6	Ccp	On boundary	Merenskyite ($PdTe_2$)	5d
Central Zone	K-22-242	476	BPKW0281M05B	5	Py	On boundary	Native gold (>75%)	5e
Central Zone	K-21-206	469.6	BPKW0031BT	26.04	Qz	Enclosed	Native gold (>75%)	5f
Central Zone	K-21-206	469.6	BPKW0031BT	30	Qz	Enclosed	Hessite (Ag_2Te)	5f
South Zone	K-22-250	200.2	BPKW0197T	1.2	Bt	Enclosed	-	6a
South Zone	K-22-250	199.8	BPKW0289M05B	0.7	Ccp-Qz	On boundary	Merenskyite ($PdTe_2$)	6b
Ultramafic rocks	K-22-247	477.6	BPKW0184BT	17.1	Cpx	Enclosed	Temagamite (Pd_3HgTe_3)	7a
Ultramafic rocks	K-22-247	477.6	BPKW0184BT	46.6	Cpx	Enclosed	Kotulskite (PdTe)	7a
Ultramafic rocks	K-22-247	477.6	BPKW0184BT	32.6	Cpx	On boundary	Sperrylite ($PtAs_2$)	7b
Ultramafic rocks	K-22-247	477.6	BPKW0184BT		Cpx	On boundary	Isomertieite ($Pd_{11}Sb_2As_2$)	7b
Ultramafic rocks	K-22-247	476	BPKW0295M06B	33.5	Cpx	On boundary	Pd-Pt mineral	7c

Abbreviations: Bt, biotite; Ccp, chalcopyrite; Cpx, clinopyroxene; MDRU, Mineral Deposit Research Unit; Py, pyrite; Qz, quartz.

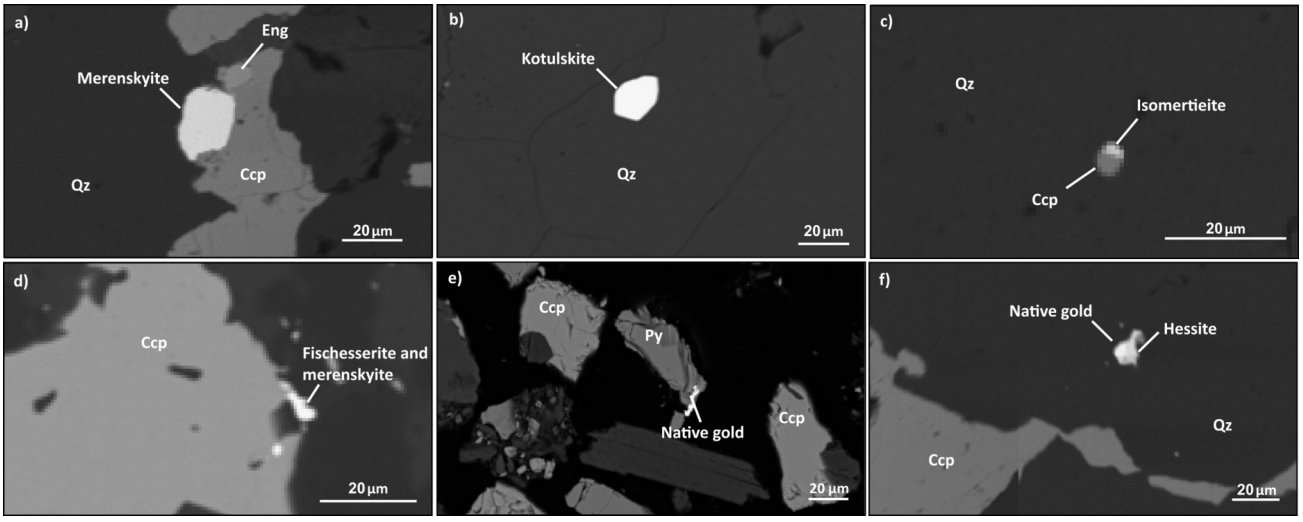

Figure 5. Scanning electron microscope (SEM) backscattered electron (BSE) images of palladium minerals and gold-silver minerals from the Central Zone of the Kwanika porphyry deposit: **a)** merenskyite ($PdTe_2$) and enargite (Cu_3AsS_4) at the boundary between chalcopyrite and quartz; **b)** kotulskite (PdTe) enclosed in quartz; **c)** isomertieite ($Pd_{11}Sb_2As_2$) at the boundary between chalcopyrite and quartz; **d)** fischesserite (Ag_3AuSe_2) and merenskyite on a chalcopyrite boundary; **e)** native gold (>75% gold) on a pyrite boundary; **f)** native gold adjacent to hessite (Ag_2Te) enclosed in quartz. Abbreviations: Ccp, chalcopyrite; Eng, enargite; Py, pyrite; Qz, quartz.

dium minerals from the literature. Backscattered electron images of these minerals are shown in Figure 6.

In the ultramafic rocks, palladium minerals, ranging in size from 0.4 to 46.6 μm^2, were primarily enclosed in clinopyroxene. Minerals containing platinum were also identified, with two grains containing both palladium and platinum minerals (32.6 μm^2 and 33.5 μm^2, respectively) at the boundary with clinopyroxene (Figure 7b, c). Electron probe microanalysis (EPMA) was conducted on one of these grains to further analyze its composition (Figure 7d). Backscattered electron images of these minerals are shown in Figure 7a–c.

Discussion

The distribution of precious minerals across different geological zones provides valuable insights into the mineralization processes within the project area. A comparison of palladium- and platinum-bearing minerals identified in this study with those discussed in the literature (Cabri, 2002) reveals five palladium-bearing minerals and one platinum-bearing mineral. Table 1 summarizes the occurrence of platinum-group minerals across geological zones. Two distinct styles of PGE mineralization are observed in the Kwanika deposit. The first is palladium dominant, occurring in monzonite and quartz monzonite hostrocks in the Central and South zones. Elevated tellurium levels, along

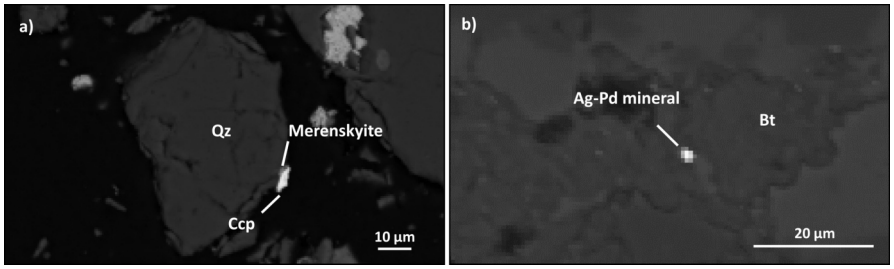

Figure 6. Scanning electron microscope (SEM) backscattered electron (BSE) images of merenskyite and a silver-palladium mineral from the South Zone of the Kwanika porphyry deposit: **a)** merenskyite ($PdTe_2$) at the boundary between chalcopyrite and quartz; **b)** silver-palladium mineral enclosed in biotite. Abbreviations: Ag, silver; Bt, biotite; Ccp, chalcopyrite; Pd, palladium; Qz, quartz.

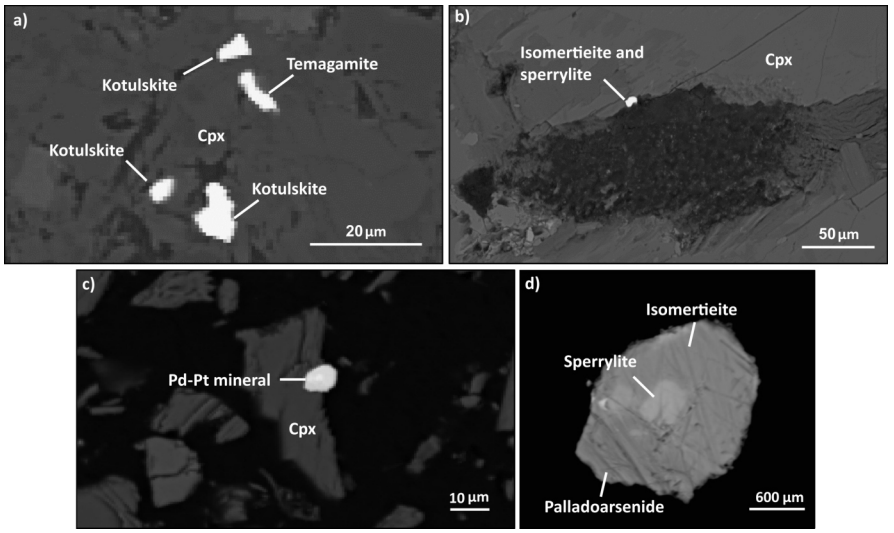

Figure 7. Scanning electron microscope (SEM) backscattered electron (BSE) images showing palladium and platinum minerals within ultramafic rocks (primarily associated with clinopyroxene) from the Kwanika porphyry deposit, including temagamite (Pd_3HgTe_3) and kotulskite (PdTe) enclosed in clinopyroxene **(a)**, isomertieite ($Pd_{11}Sb_2As_2$) and sperrylite ($PtAs_2$) on the boundary with clinopyroxene **(b)**, a palladium-platinum mineral on the boundary with clinopyroxene **(c)** and an electron probe microanalysis (EPMA) image of the palladium-platinum mineral from image (c) showing isomertieite ($Pd_{11}Sb_2As_2$), sperrylite ($PtAs_2$) and palladoarsenide (Pd_2As) in a complex grain **(d)**. Abbreviations: Cpx, clinopyroxene; Pd, palladium; Pt, platinum.

with the occurrence of platinum-group minerals at sulphide-silicate boundaries or enclosed within hydrothermal quartz and sulphides, suggest a process similar to the semi-metal collector mechanism proposed for the Skouries porphyry deposit (McFall et al., 2018); this mechanism likely facilitated the transport and concentration of PGEs in these zones. Furthermore, a significantly higher abundance of gold-silver minerals in the Central Zone and the association of platinum-group minerals with gold-silver minerals in the Central and South zones suggest that PGEs, gold and silver were transported by the same telluride melt. The second PGE style is palladium and platinum dominant, confined to hornblende pyroxenite, with little to no sulphide mineralization. Absence of gold-silver minerals, low tellurium content and platinum-group minerals (kotulskite, isomertieite, sperrylite, temagamite and palladoarsenide) enclosed in clinopyroxene indicate a magmatic origin.

Conclusion

The Kwanika porphyry deposit exhibits an unusual enrichment in platinum-group elements, characterized by three distinct geological zones. Six types of platinum-group minerals that average 22 μm² in size are identified in the deposit. Two distinct styles of platinum-group element mineralization are identified; palladium dominant in the Central and South zones, and palladium and platinum dominant in the ultramafic rocks. This study constitutes part of a broader investigation into platinum-group element and gold deportment in the Kwanika deposit. Ongoing research will focus on the geological factors controlling palladium and gold precipitation, and the interplay between these two styles of platinum-group element mineralization. Future studies will also address the potential for lattice-hosted platinum-group elements.

Acknowledgments

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