Textural evidence for ore fluid transport and the magmatic to hydrothermal transition at the past-producing Kitsault Mo-Ag mine

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Abstract

The Kitsault Mo-Ag mine is a low-F porphyry Mo-Ag deposit hosted in Paleogene rocks of the Lime Creek intrusive complex. This complex consists of multiple stocks and plugs of quartz diorite to quartz monzonite that are surrounded by a broad zone of biotite hornfels developed in argillite and greywacke of the Bowser Lake Group. Molybdenum mineralization defines a cylindrical mineralized body that is in part spatially coincident with a series of aplite dikes with disequilibrium textures (unidirectional solidification textures, pegmatites, miarolitic cavities). The Mo grade shell has been disrupted internally by a late phase of quartz monzonite porphyry (quartz monzonite porphyry II) that lacks aplite. A series of unmineralized biotite- and hornblende-phyric lamprophyre dikes crosscuts all phases of the Lime Creek intrusive complex and surrounding Bowser Lake Group sedimentary rocks. The disequilibrium textures observed in the aplite dikes are interpreted to represent a permeable structure that focused ore-bearing fluids along the aplitic crystal mush, which episodically released during pressure fluctuations. This mechanism is consistent with a spatial coincidence between aplite dikes and Mo mineralization, internal veins, and disequilibrium textures within the aplite dikes.

Keywords: Kitsault Mo-Ag deposit, low-F porphyry Mo, magmatic to hydrothermal transition, unidirectional solidification textures

1. Introduction

Molybdenum is considered a critical mineral in Canada (Natural Resources Canada, 2022). It is an essential element used in steel production and found in many components of wind turbines, and is, therefore, considered a valuable commodity for the transition to a low-carbon economy. Porphyry deposits are the main host of Mo worldwide (~95%), where it occurs as a co-product or by-product in porphyry Cu deposits, or as the principal commodity in porphyry Mo deposits (Sinclair, 2007; John and Taylor, 2016). British Columbia is the only province that produces Mo in Canada where it has been produced predominantly from porphyry Mo deposits (e.g., Endako, Kitsault, Boss Mountain) and, to a lesser extent, porphyry Cu deposits (e.g., Gibraltar, Highland Valley Copper; Clarke et al., 2024). Because porphyry Mo deposits are the most significant source of Mo in British Columbia, understanding their genesis and potential to host other critical minerals (e.g., Ag, W, Cu, and Zn), is important for the provincial economy.

In British Columbia, most porphyry Mo deposits are the arc-related, low-F variety. The largest, and type locality for this deposit class is the well-studied Endako deposit (Jurassic), which produced 253,228 t of Mo since 1965 (Carr, 1966; Bysouth and Wong, 1995; Selby et al., 2000; Selby and Creaser, 2001; Whalen et al., 2001; Villeneuve et al., 2001). Other low-F porphyry Mo deposits in British Columbia are less well studied, the most significant of which is the Kitsault Mo-Ag deposit (Paleogene) with NI 43-101 compliant Measured and Indicated resources of 321,800,000 t at 0.071% Mo (228,478 t of contained Mo; Fulton, 2014). The Kitsault deposit was mined for Mo between 1967 and 1972, and stockpiled ore was processed on site during 1981 and 1982. The most recent study published on Kitsault summarized the geology, alteration and vein stages (Steininger, 1985), K-Ar ages were determined by Carter (1981), and incremental work that improves upon the geological map and geochemical character of the deposit has been presented in several assessment reports since (Barresi, 2011; Fulton, 2014).

Magmatic-hydrothermal disequilibrium textures are commonly found in porphyry Mo deposits (e.g., Shannon et al., 1982 Lowenstern and Sinclair, 1996). These textures can be used by exploration geologists as pathfinders to economic mineralization (e.g., Shannon et al., 1982; Lowenstern and Sinclair, 1996; Bain et al., 2022) and provide insight into deposit-forming processes (e.g., Carter et al., 2021). As part of fieldwork in 2023 at Kitsault, we observed many of these textures (e.g., unidirectional solidification textures, miarolitic cavities, pegmatites) that were not previously recognized. This paper forms a preliminary study based on field and hand sample observations to determine crosscutting relationships and identify magmatic and hydrothermal features that can be used to interpret the paragenesis and potential mechanisms of ore formation. This work was carried out in the Nass Area and Nass

Wildlife Area as described in the Nisga'a Final Agreement, and on the traditional territories of the Northern Tsimshian.

2. Regional geology

The Kitsault mine is in the Intermontane superterrane along its western boundary with the Coast Plutonic complex of the Insular superterrane (Figs. 1, 2). The Intermontane superterrane includes an assemblage of multi-phase volcanic island arc terranes (e.g., Stikinia and Quesnellia) that accreted onto the western margin of Ancestral North America in the Middle Jurassic (Nelson and van Straaten, 2020; George et al., 2021; Nelson et al., 2022). The Coast Plutonic complex consists of a range of granitic rocks that were emplaced during the Jurassic to Paleogene (Gehrels et al., 2009; Brown, 2020). Overlying these belts are the eroded remnants of Recent plateau-lava flows. The Kitsault mine is within the so-called Golden Triangle (Fig. 1), a loosely defined metal-rich area delineating a region in west central Stikinia that contains significant copper-gold-silver-molybdenum resources.

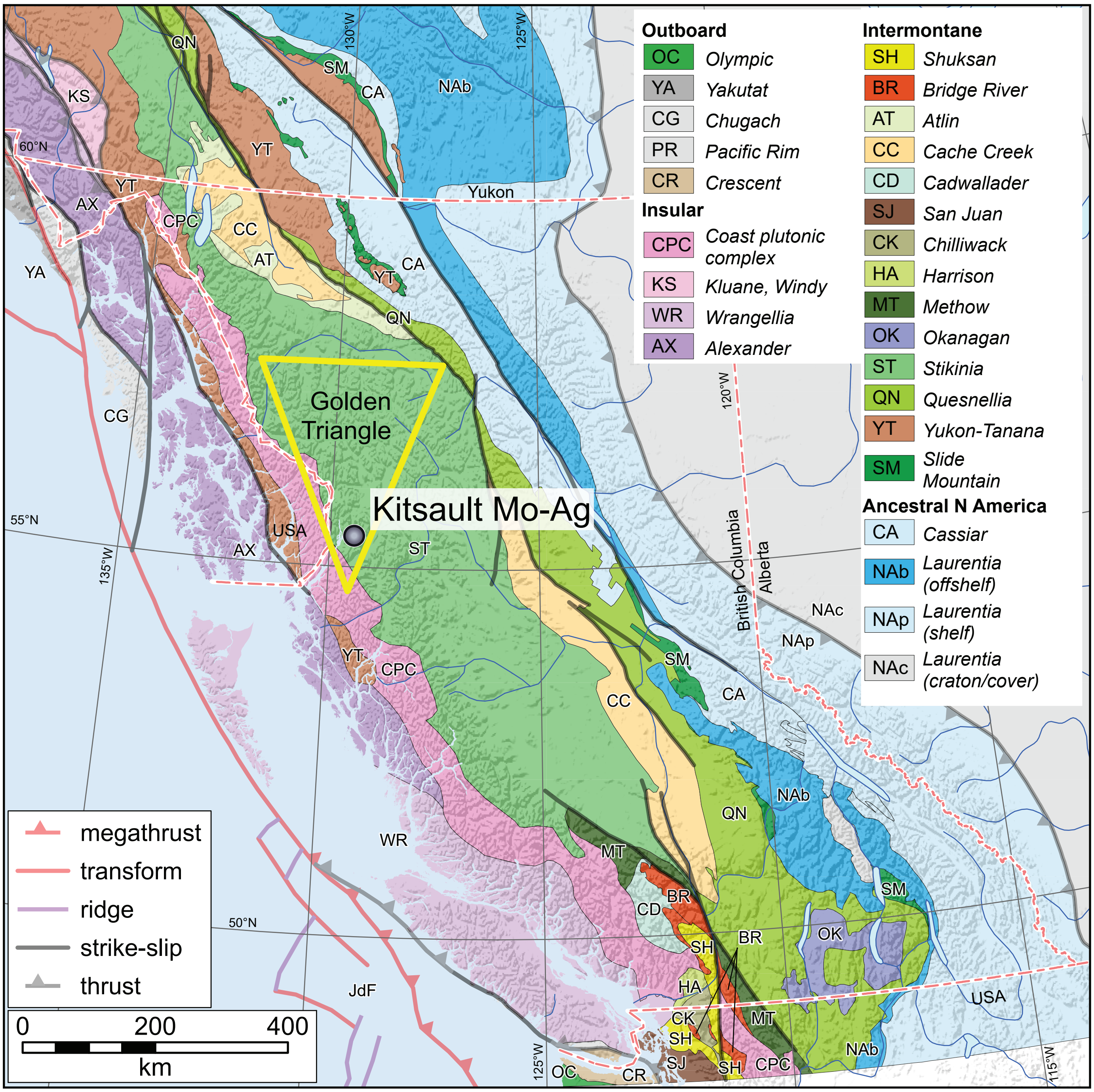

Fig. 1. Location of Kitsault Mo-Ag porphyry mine and the Golden Triangle. Terranes after Colpron (2020).

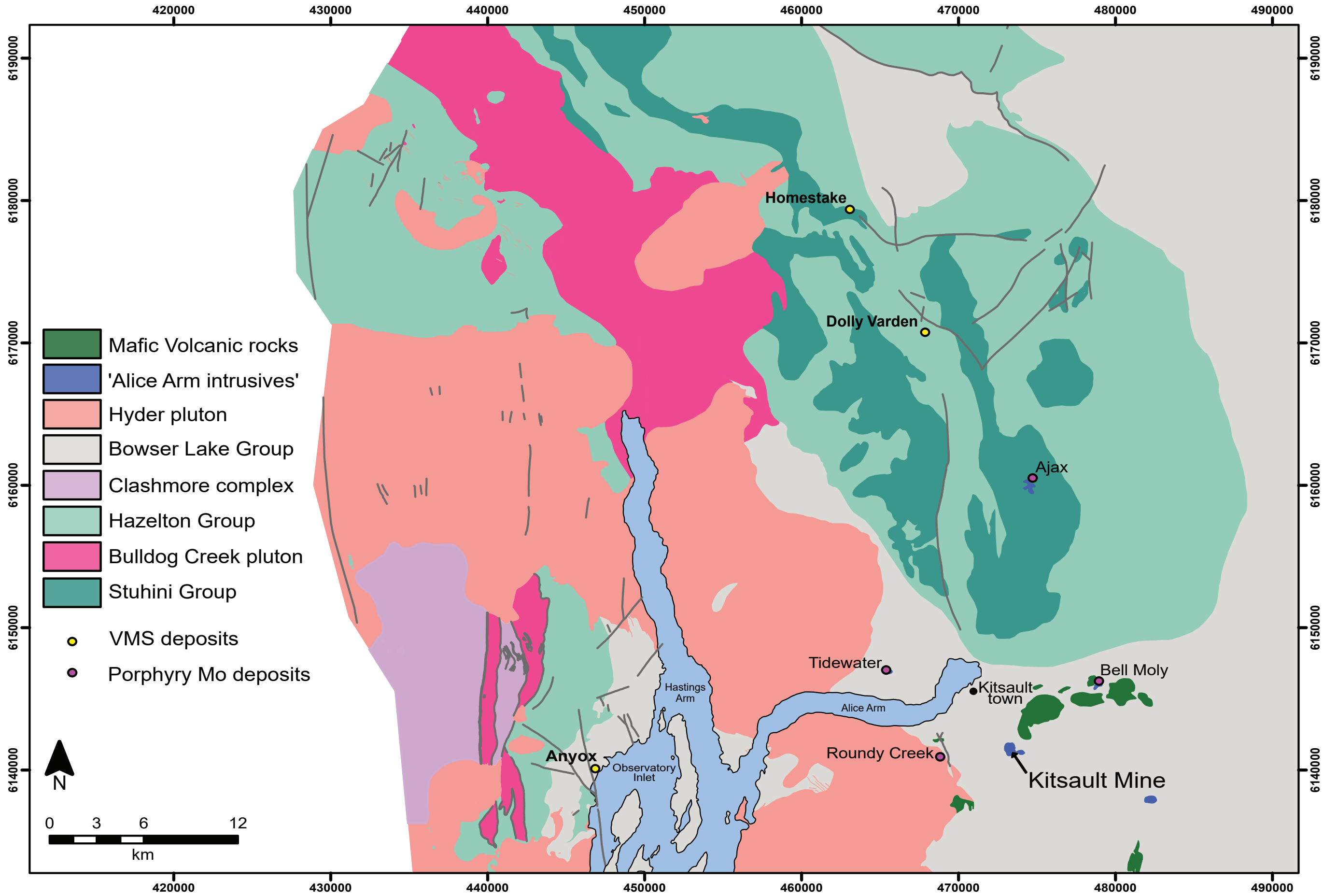

Fig. 2. Regional geology of the Kitsault Mo-Ag mine with selected porphyry Mo, and volcanogenic massive sulphide deposits. NAD83, UTM zone 9. Modified after Colpron and Nelson (2011).

In the Kitsault area (Fig. 2), stratified units include the Bowser Lake Group (Upper Jurassic), which consists of interbedded greywacke and argillite with minor limestone and conglomerate (Steininger, 1985). A suite of Coast Plutonic complex granodiorite to quartz monzonite stocks, commonly referred to as the 'Alice Arm intrusives', were emplaced between 55 and 50 Ma (Carter, 1981). Some of these stocks host Mo, including Kitsault, Roundy Creek, Bell Moly, Tidewater, and Ajax (Fig. 2). Post-mineralization, a swarm of 36 to 34 Ma, northeast-striking, lamprophyre dikes intruded the Bowser Lake Group and Alice Arm intrusives. The youngest igneous rocks in the area are 1.60 to 0.62 Ma plateau-type basaltic flows and related vesicular dikes (Steininger, 1985).

3. Kitsault Mo-Ag deposit

The Kitsault Mo-Ag mine is a low-F porphyry Mo deposit 6 km southeast of the town of Kitsault (Fig. 2). The mine site is approximately 600 m above sea level in an area of significant relief. Molybdenum mineralization is manifested as disseminations, quartz vein stockworks, and sheeted vein arrays that define a cylindrical mineralized body (Figs. 3, 4). This body has an internal barren core, 100-150 m wide on its east, west, and north sides, and at least 300 m wide on its south side. For this study, we logged and sampled 15 drill holes (A-A', B-B'; Figs. 3, 5). These holes were drilled post-mining by Avanti Mining Ltd in 2008 and 2011 and intersect the Lime Creek intrusive complex and sedimentary rocks of the Bowser Lake Group (Figs. 3, 5). We collected 158 samples for further petrographic and geochemical study.

Surrounding the Lime Creek intrusive complex, the Bowser Lake Group consists of variably hornfelsed interbedded argillite and greywacke with lesser conglomerate and limestone (Figs. 3, 6a). Steininger (1985) determined that the argillite and greywacke consist of variable proportions of plagioclase, quartz, chert, sericite, and chlorite. The sedimentary rocks have been thermally altered up to 750 m from the contact with the Lime Creek intrusive complex (Fig. 3). The hornfels is zoned from a weakly developed albite-epidote outer zone, to a medial moderately developed biotite zone, to an inner zone that has more intensely developed biotite (Fig. 6a). In the biotite hornfels zones, calcareous horizons have been altered to skarn consisting of epidote, carbonate, and garnet.

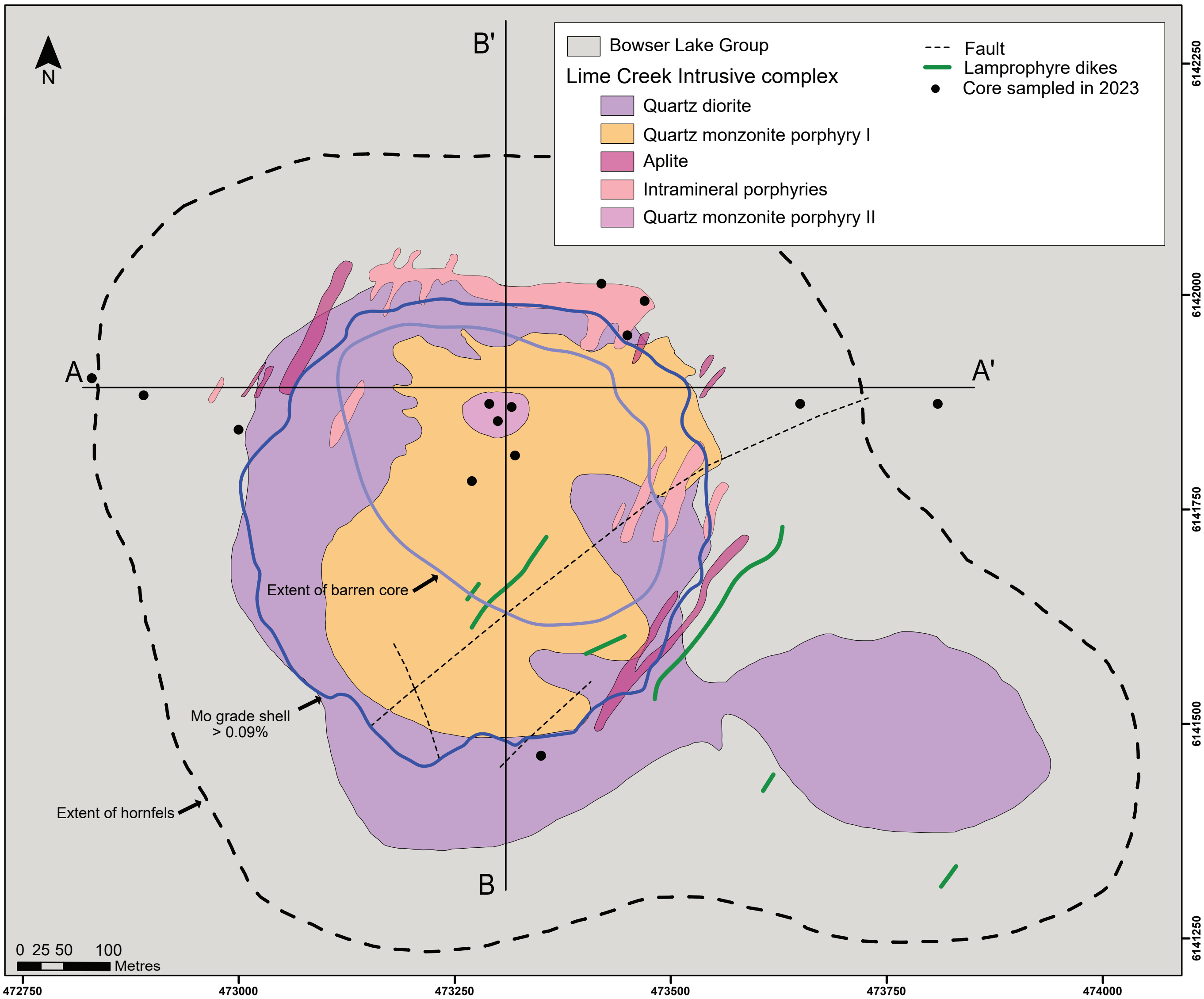

Fig. 3. Relationships of phases in the Lime Creek intrusive complex, Mo grade shell, and extent of the barren core. See Figure 5 for cross sections A-A' and B-B'. NAD83, UTM zone 9. Modified after Fulton (2014).

3.1. Lime Creek intrusive complex

In this study, the intrusive rocks have been named according to the most recent technical reports (Barresi, 2011; Fulton, 2014). The intrusive complex largely consists of equigranular to variably porphyritic granitic rocks consisting of feldspar, quartz, and biotite. Three major phases have been delineated, including quartz diorite, quartz monzonite porphyry I, and quartz monzonite porphyry II (Figs. 3, 5, 6).

Quartz diorite is the oldest phase. It can be distinguished based on its darker appearance, equigranular texture, and presence of minor amphibole (Figs. 6b, d). Quartz diorite encircles quartz monzonite porphyry I and is the unit most observed in contact with the surrounding hornfelsed argillite and greywacke of the Bowser Lake Group (Figs. 3, 5). Quartz monzonite porphyry I crosscuts quartz diorite, forming an embedded ~500 m-wide plug (Figs. 3, 5). The plug has steeply outward-dipping contacts with the enclosing quartz diorite. The contacts are locally obscured by hydrothermal alteration, but where visible are sharp (Fig. 6d). Both quartz diorite and quartz monzonite porphyry I host Mo mineralization and are crosscut by many of the vein stages, showing no changes in Mo grade at or across the contacts (Fig. 3). Quartz monzonite porphyry II apparently postdates most of the economic Mo mineralization but is crosscut by quartz-carbonate veins (Fig. 7g). This unit has a more conspicuous porphyritic appearance than quartz diorite and quartz monzonite porphyry I (Fig. 6) and can also be distinguished by the presence of feldspar rafts and a greater abundance of quartz phenocrysts (Fig. 6e). This unit forms an elliptical plug roughly coincident with the barren core of the deposit (Figs. 3-5).

A variety of dikes have been observed within and surrounding the Lime Creek intrusive complex. Sets of well-mineralized

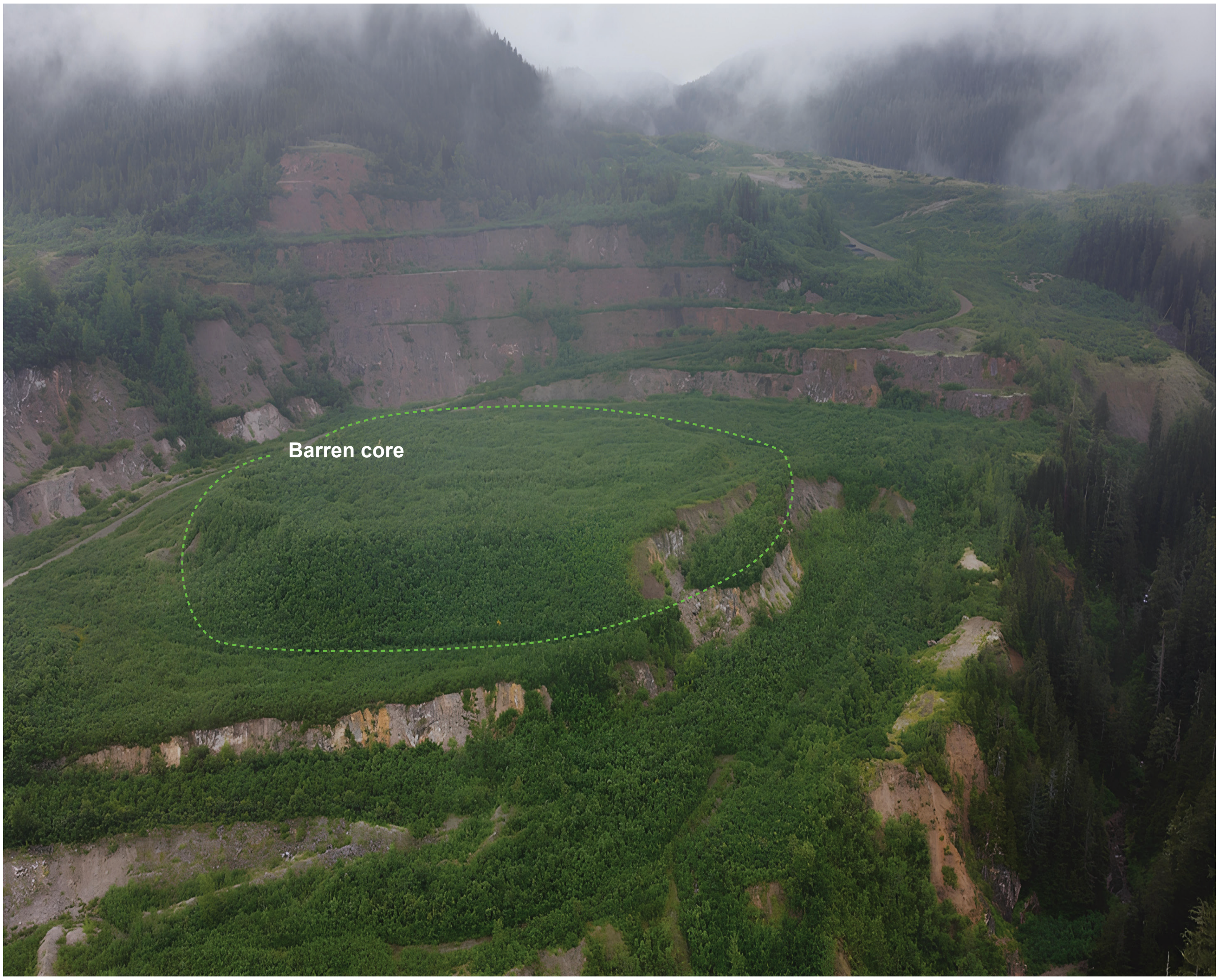

Fig. 4. Aerial photograph taken from a drone in 2023. The image shows the Kitsault Mo-Ag mine and an outline of the barren core depicted in Figure 3. View to the west.

aplite dikes crosscut the quartz diorite and quartz monzonite porphyry I but are absent in the quartz monzonite porphyry II (Figs. 3, 7g). Based on observations made during drill core logging, these dikes are the only unit to contain molybdenite disseminations and are spatially coincident with abundant quartz-molybdenite veins (Carter, 1981; Fulton, 2014). These north-striking dikes have been mapped along strike for 15-75 m (Fulton, 2014), and have been observed in drill core to have apparent widths of 0.5-15 cm. These dikes can cluster, forming sheeted zones with a cumulative width of 10 m or more (Fulton, 2014).

The aplite dikes locally have a sucrose texture, but they also present as pegmatitic pods of K-feldspar and quartz (Fig. 7e). Elsewhere, layers of quartz are apparently semi-parallel, wavy, heterogranular, and monomineralic (cf. Müller et al., 2023) and are interlayered with aplite (Figs. 7c-f). Some quartz layers have a more irregular form showing diffuse margins (Figs. 7a, c). Near some of the quartz layers, irregular shaped cavities have formed that are lined with inward projecting crystals of quartz (Fig. 7f). These features are the oldest observed segregations of quartz observed at Kitsault and are crosscut by every quartz-bearing vein stage.

A separate set of dikes has been referred to as “Intramineral dikes” by Steininger (1985) and Fulton (2014). The affinity of the “Intramineral dikes” is not well known; they have been hypothesized to be related to quartz monzonite porphyry II on the basis of texture, chemistry, and spatial relationships (Steininger, 1985). Our preliminary observations suggest that they have been subjected to more intense hydrothermal alteration and veining than the quartz monzonite porphyry II and can be distinguished by the presence of amphibole and less biotite (Figs. 6f, 7g). The youngest intrusive phase observed at Kitsault during this study consists of northeasterly striking, 0.5 to 10 m-wide biotite- and hornblende-phyric lamprophyre

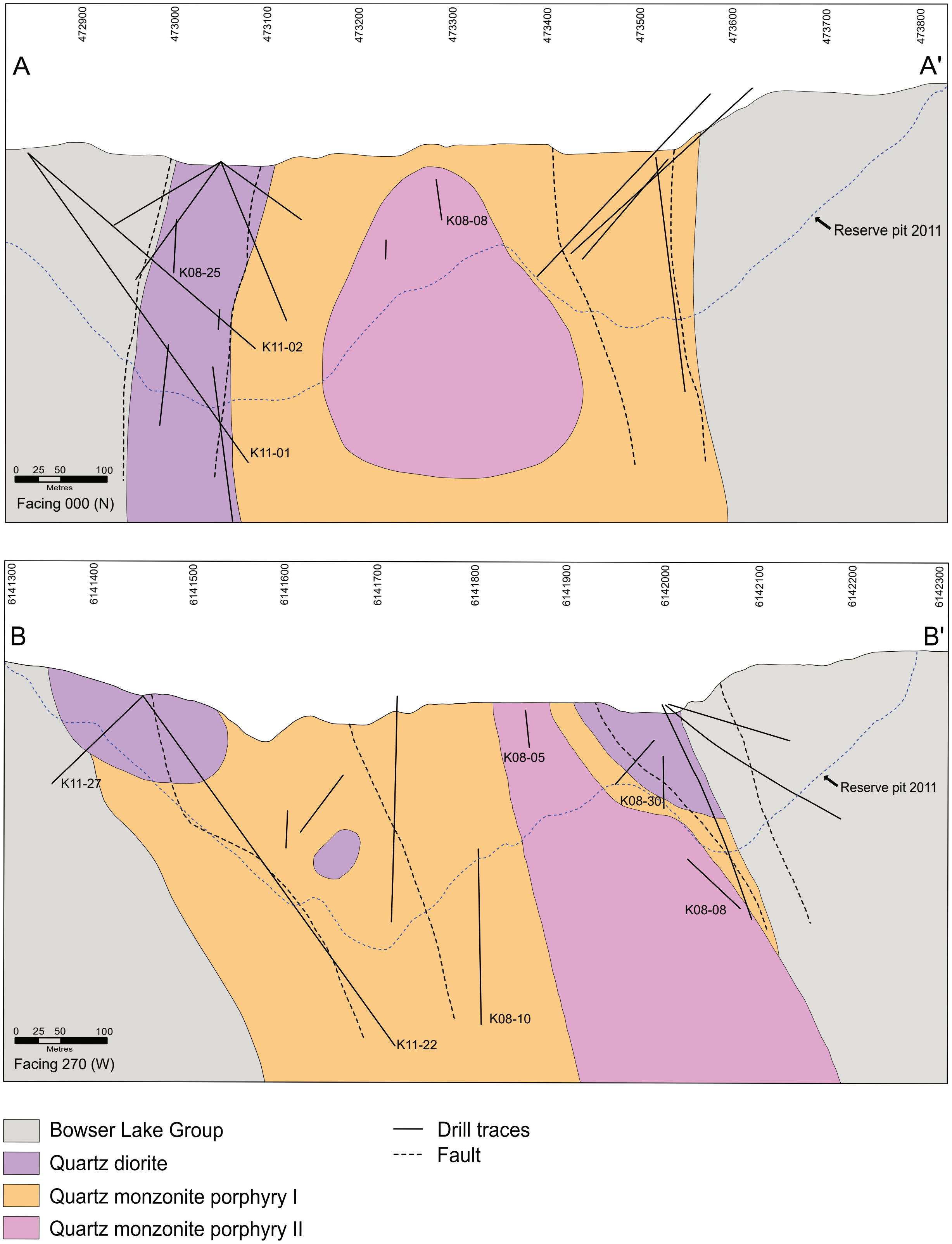

Fig. 5. Cross sections of the Kitsault mine; see Figure 3 for locations. Labelled drill traces represent holes sampled in 2023. The trace of the 2011 reserve pit indicates previously economic Mo grade. The quartz monzonite porphyry II is spatially coincident with the barren core of the deposit. The aplite, intramineral porphyries, and lamprophyre dikes, which are all narrow, apparently sporadic, and difficult to trace between drill holes are not shown. The aplite dikes and intramineral porphyries mainly occur within quartz diorite and quartz monzonite porphyry I, with narrow branches observed crosscutting the Bowser Lake Group sedimentary rocks. The lamprophyre dikes crosscut every phase of the Lime Creek intrusive complex and the Bowser Lake Group. NAD83, UTM zone 9.

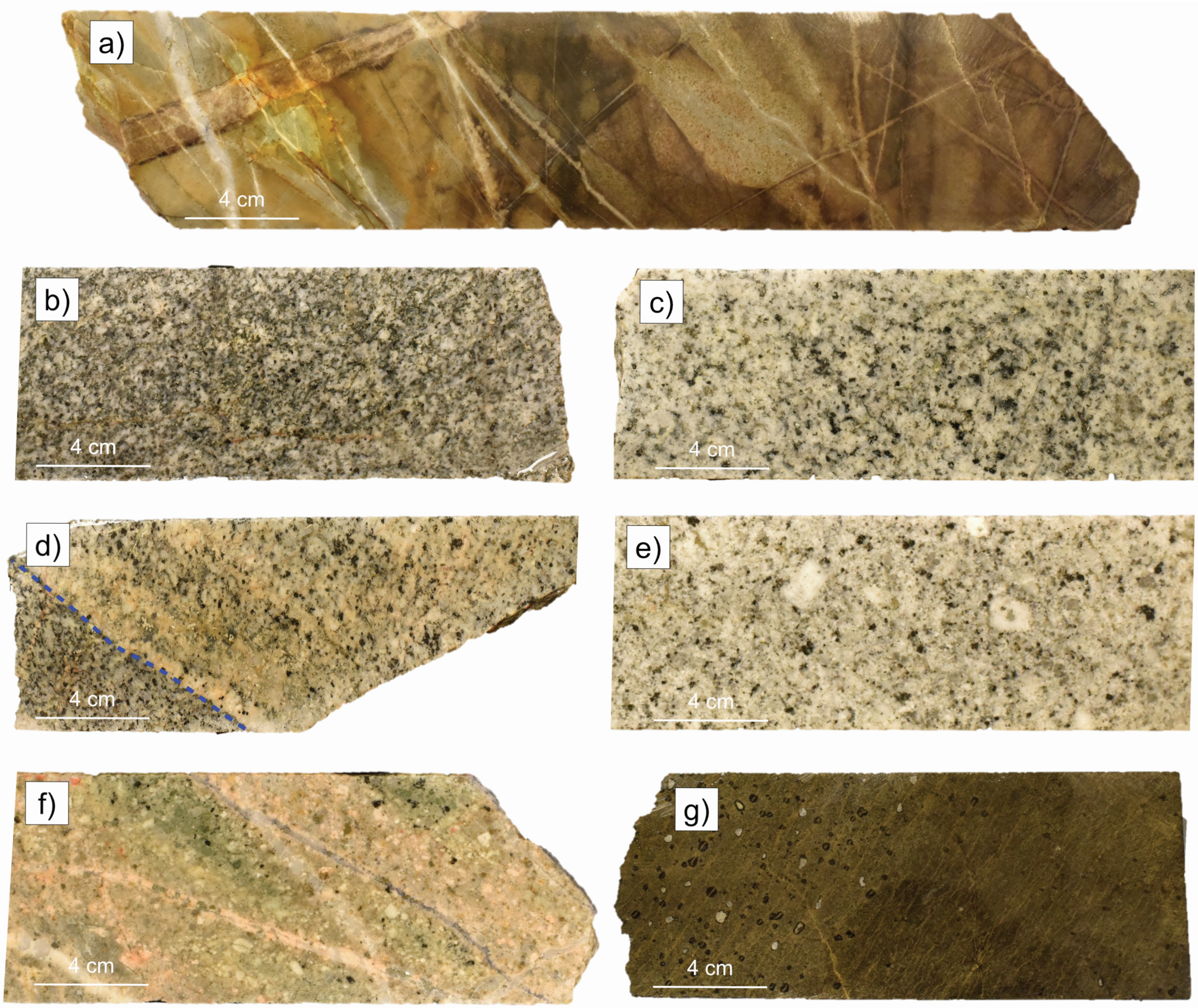

Fig. 6. Representative drill core photographs of the main rock types found at the Kitsault Mo-Ag deposit. **a)** Biotite hornfels greywacke containing fine-grained, disseminated pyrite and numerous quartz veins. **b)** Quartz diorite. **c)** Quartz monzonite porphyry I. **d)** Contact between quartz monzonite porphyry I and quartz diorite (the blue dashed line delineates the contact). **e)** Quartz monzonite porphyry II. **f)** Intramineral porphyry. **g)** Lamprophyre.

dikes (Figs. 3, 6g). These dikes crosscut every phase of the Lime Creek intrusive complex and the surrounding Bowser Lake Group sedimentary rocks (Fig. 3). The lamprophyres do not contain any molybdenite mineralization. They are crosscut by rare calcite veins (Steininger, 1985).

3.2. Veins

We observed four distinct hydrothermal vein stages. The oldest observed vein stage is quartz-molybdenite±pyrite veinlets, veins and stockworks that are well developed within and surrounding the aplite dikes (Figs. 7a-c), but rare or absent in the quartz monzonite porphyry II (Fig. 7g). Some of the quartz-molybdenite veins appear to originate internally to the aplite dikes, and can present subparallel or oblique, and in some cases are truncated at the dike margins (Figs. 7a-c). Many of these veins have K-feldspar±biotite halos, making up a significant amount of the potassic alteration observed in this study (Fig. 7h). Subparallel, 3-20 cm-wide, sheeted 'ribbon' quartz veins containing epitaxial bands of fine-grained molybdenite occur within the quartz diorite and quartz monzonite porphyry I (Fig. 8a), but do not occur within the aplite.

Pyrite veins and veinlets with subordinate molybdenite and quartz occur mostly within the hornfelsed argillite and greywacke (Fig. 8b). These structures locally have pyrite-sericite-quartz halos and have not been observed in direct relationship with the above quartz veins. The youngest vein stage observed in this study consist of quartz-carbonate

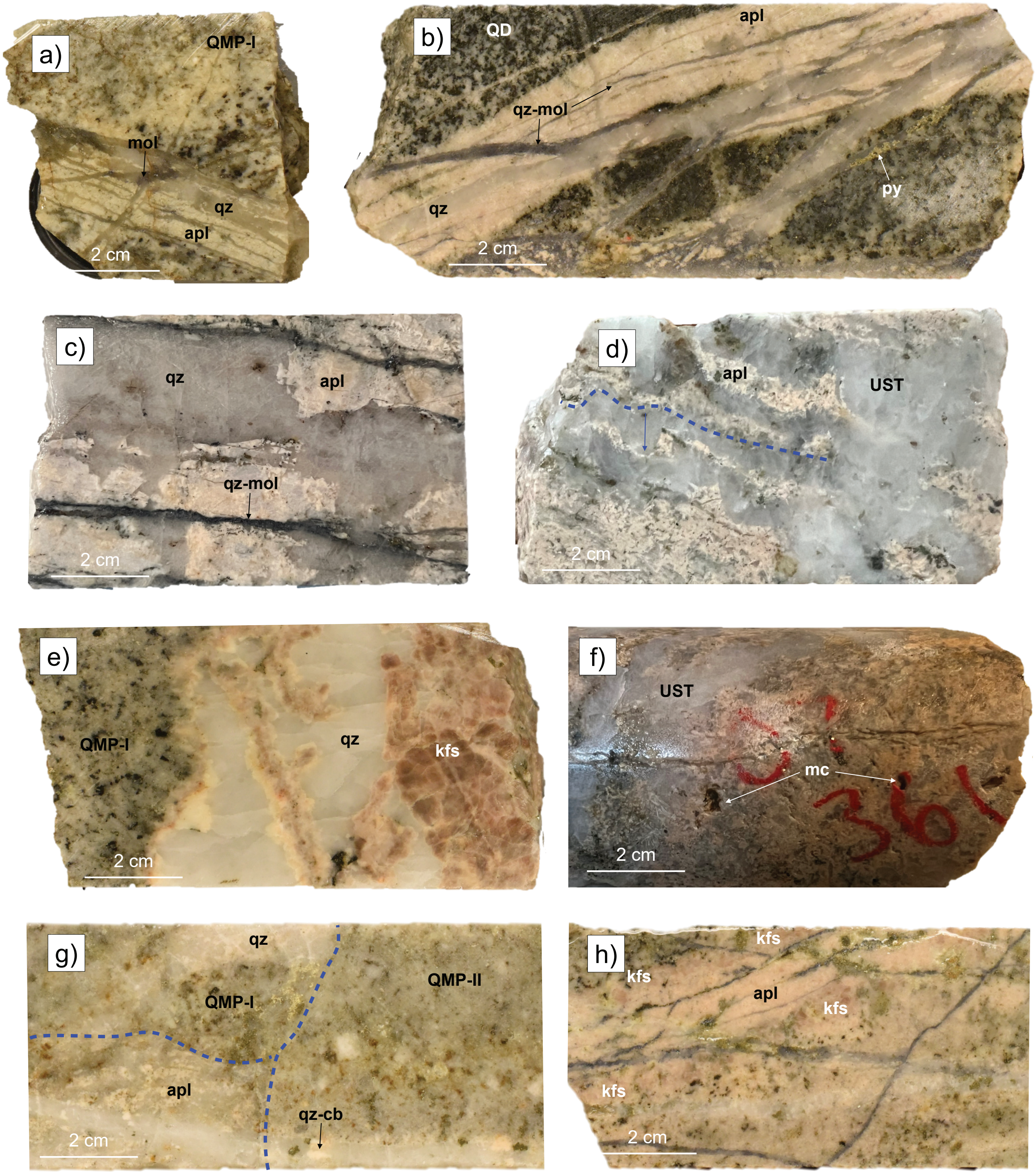

Fig. 7. Drill core photographs of aplite dikes and disequilibrium textures at the Kitsault Mo-Ag deposit. **a)** 2 cm-wide dike of interfingering aplite and quartz in quartz monzonite porphyry I, indicating mingling of magmatic silicate liquids and hydrothermal fluids. **b)** 4 cm-wide mineralized aplite dike with early quartz layers with diffuse margins, and quartz-molybdenite veins (with pyrite) locally internal to the aplite body and at low angles to the dike walls. **c)** Aplite dike with early quartz crosscut by quartz-molybdenite veins. **d)** Sequence of unidirectional solidification textures (UST; blue arrow marking c-axis) in an aplite dike, indicating rapid pressure fluctuations during dike emplacement. **e)** Pegmatite with K-feldspar and quartz. **f)** Miarolitic cavities on the backside of the sample in Figure 7d showing a close spatial relationship between miarolitic cavities and USTs. **g)** Three-way contact between aplite, QMP-I, and QMP-II (blue dashes). The QMP-II truncates the aplite and most quartz veins. A quartz-carbonate vein crosscuts aplite and QMP-II. **h)** Aplite dike with intensely developed K-feldspar alteration.
Abbreviations: apl – aplite, kfs – K-feldspar, mc – miarolitic cavity, mol – molybdenite, py – pyrite, QD – quartz diorite, QMP-I – quartz monzonite porphyry I, QMP-II – quartz monzonite porphyry II, qz – quartz, qz-cb – quartz-carbonate vein, qz-mol – quartz-molybdenite vein, UST – unidirectional solidification textures.

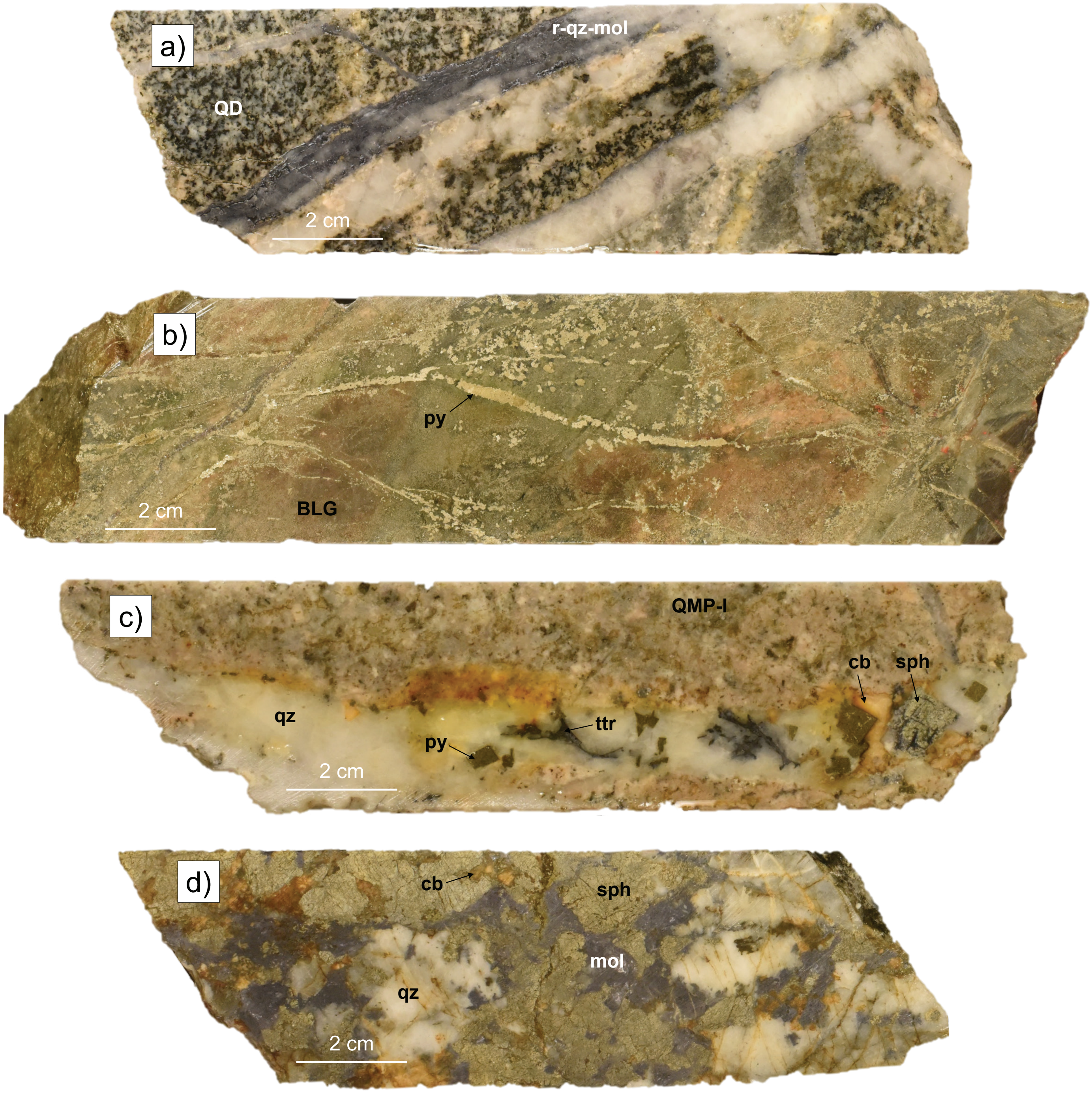

Fig. 8. Drill core photographs of vein stages at the Kitsault Mo-Ag deposit. **a)** Ribbon quartz-molybdenite vein crosscutting quartz diorite. These veins are typically >1.5 cm-wide and contain multiple epitaxial bands of molybdenite alternating with quartz. **b)** Bowser Lage Group sedimentary rock crosscut by pyrite veins and veinlets. **c)** 2 cm-wide polymetallic quartz-carbonate vein that is predominantly quartz with subordinate carbonate, sphalerite, pyrite and tetrahedrite. **d)** >8 cm-wide polymetallic quartz-carbonate vein that is predominantly sphalerite, quartz, and molybdenite with subordinate carbonate and pyrite.
Abbreviations: BLG – Bowser Lake Group, cb – carbonate, mol – molybdenite, QD – quartz diorite, r-qz-mol – ribbon quartz-molybdenite vein, sph – sphalerite, ttr – tetrahedrite.

with variable amounts of sphalerite, galena, chalcopyrite, molybdenite and Pb-Bi sulphosalts (Figs. 8c, d). These veins are best developed on the south side of the deposit and crosscut every unit except for the lamprophyre dikes.

4. Discussion

4.1. Magmatic to hydrothermal transition

Unidirectional solidification textures (USTs) can act as useful pathfinders to mineralization in porphyry deposits (Shannon et al., 1982; Lowenstern and Sinclair, 1996; Bain et al., 2022; Müller et al., 2023). Rather than being considered veins, they are layers of hydrothermal or magmatic crystals (typically quartz) with a common growth direction (hence unidirectional), perpendicular to lithological interfaces. These quartz layers crystallize from an exsolved, magmatic fluid/melt that accumulated at the top or margins of shallow intrusions (Lowenstern and Sinclair, 1996; Seo et al., 2021). The fluid/melt act as a medium for rapid diffusion and transport of silica from the crystallizing magma to the growing quartz layers (Müller et al., 2023), and formation of successive quartz UST layers may result from cyclical fluctuations in the P-T-X conditions of this fluid/melt. A mechanism to reduce pressure rapidly is by hydraulic fracturing of the wall-rock (e.g., Candela, 1989), which allows fluid escape through accommodating structures, and then portions of the underlying melt quench against the quartz layer as aplite. These escape structures then heal due to mineral precipitation resulting in renewal of hydrostatic pressure build up, and quartz then nucleates on the newly formed aplite and grows toward the volatile-rich, over-pressured environment. Hydrostatic pressure continues to build until the process is repeated. This is the first study to document similar structures at Kitsault (Fig. 7d). These interpreted USTs are similar to textures observed at the Henderson Mo mine (Shannon et al., 1982). Further petrographic work is required to confirm what other minerals are present (e.g., molybdenite or other sulphides and oxides) and determine intricate growth sequences. The formation of USTs is the first stage of melt segregation from a crystal mush that sequesters metals from silica melts leading to the subsequent precipitation of the metals, which is consistent with the abundant early quartz-molybdenite veins that crosscut the aplite dikes at Kitsault (Figs. 7b, c).

Unidirectional solidification textures are only one type of disequilibrium texture associated with the magmatic to hydrothermal transition that can occur in porphyry deposits. At Kitsault, USTs occur together with pegmatite segregations (Fig. 7e) and cavities (Fig. 7d), that are interpreted here to be miarolitic cavities due to their irregular shape, inward-projecting crystals and close spatial relationship with USTs (e.g., Candela, 1997). Miarolitic cavities are formed by bubble growth during magma ascent and are locked in place by the rapid quenching of the melt due to decompression (Candela, 1997); they are direct evidence for volatile phase saturation and exsolution. Pegmatites in the aplite dikes are composed of coarse K-feldspar and quartz crystals (Fig. 7e) and indicate that the melt was subjected to undercooling (e.g., London, 1992; London and Morgan, 2012). Together, these features indicate melt immiscibility, volatile exsolution and enrichment at the apex and margins of the aplite dikes.

4.2. Fluid transport in crystal mush dikes

There are no observed magmatic-hydrothermal features in the early Lime Creek intrusives (quartz diorite, quartz monzonite porphyry I, quartz monzonite porphyry II) to suggest exsolution of mineralizing fluids (e.g., miarolitic cavities, USTs, internally derived veins), and there are no abrupt changes in vein abundance at intrusive contacts. These intrusives are crosscut by quartz-molybdenite veins and other mineralization (Figs. 7a, c), but the source of the fluids is likely from elsewhere. Therefore, these intrusions are interpreted as a passive host to mineralization at Kitsault.

Multiple generations of aplite dikes occur throughout the Kitsault deposit. They typically crosscut the quartz diorite and quartz monzonite porphyry I, but have an unclear relationship with the intramineral porphyry dikes (Fig. 7g). The aplite dikes are truncated by the quartz monzonite porphyry II (Fig. 7g). The aplite dikes contain magmatic to hydrothermal transition textures (e.g., USTs, pegmatite segregations, miarolitic cavities; cf. 'vein dikes' from Henderson Mo deposit; Shannon et al., 1982; Kirkham and Sinclair, 1988), as well as disseminated molybdenite mineralization indicating that they formed contemporaneous with early- to syn-mineralization. Based on field observations, the potassic alteration and quartz-molybdenite veining at Kitsault is well developed and typically intense surrounding the aplite dikes, suggesting that they contributed significantly to hydrothermal alteration and substantive hypogene mineralization. The presence of interfingering aplite and quartz segregations that appear to pinch and swell within the aplite dikes (cf. 'parting veins', which are quartz veins that contain numerous septa or partings of aplite; Kirkham and Sinclair, 1988; Figs. 7a, b), as well as early internal, continuous and irregular quartz veins that are subparallel and locally bound by the aplite margins suggests there is a hydrothermal component (Figs. 7a, b); whereas aplite is generally considered to be of entirely magmatic origin. These textures together suggest that the aplitic melts functioned as a magmatic crystal mush framework producing fluid exsolution (e.g., evidenced by the miarolitic cavities). This interconnected permeable framework may have acted as a conduit for the upward migration of pressurized mineralizing fluids from an underlying parent magma (e.g., Carter et al., 2021).

5. Conclusions

The Lime Creek intrusive Complex, which hosts the Kitsault Mo-Ag porphyry deposit, intruded the Bowser Lake Group sedimentary rocks during the Paleogene, and exhibits a variety of magmatic-hydrothermal disequilibrium textures that provide insights into the mechanisms that formed the deposit. Upward emplacement of quartz diorite to quartz monzonite magmas formed numerous generations of porphyry stocks and aplite dikes, which have complex relationships with mineralization.

Fluid/melt flow and crystallization within the aplite dikes during periods of pressure change and undercooling likely formed layers of USTs, and resultant fluid exsolution formed miarolitic cavities. The aplite structures acted as an important pathway for at least some of the fluid-saturated magmas and ore fluids at Kitsault to migrate through the deposit. Further work is required to identify other mechanisms that focused Mo-rich ore fluids. Some of the porphyry-style mineralization was focused as narrow zones around the aplite dikes, which was largely disrupted by a late mineralization quartz monzonite stock lacking mineralized aplite (quartz monzonite porphyry II).

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