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Front cover: Merry Widow past-producing pit; massive sulphide gossan in foreground. **Photo by W.M. Bain.**

Back cover: Massive magnetite ore bodies in volcanic host rocks, Merry Widow past-producing pit. **Photo by W.M. Bain.**

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Abstract
Iron skarns are a distinct subtype in the skarn class of deposits characterized by massive magnetite orebodies with variable Co-bearing sulphide mineralization. The Wrangel terrane of western British Columbia has several Co-bearing iron skarns, including the Merry Widow deposit on northern Vancouver Island. The Merry Widow deposit contains several large sulphide-bearing, magnetite-calcite orebodies and numerous other minor massive sulphide occurrences. Both host minor Co mineralization in the form of sulphide and arsenide minerals. This deposit also has several distinctive textural and mineralogic features, including: 1) banded and tabular magnetite-calcite ores; 2) zones of massive, euhedral calcite that are always associated with sulphide mineralization; 3) tabular sulphide masses adjacent to mafic dikes; and 4) calc-silicate and carbonate-bearing sodic alteration that occurs predominantly in intrusive and volcanic rocks.

Keywords: Critical minerals, cobalt, iron skarns, Wrangellia, Vancouver Island, magnetite

1. Introduction

Skarn deposits have received recent global attention from the mineral exploration industry because they commonly contain critical minerals needed for the transition to low-carbon economies. Critical minerals such as Zn, W, Sn, Mo, and Cu can be mined from skarns as primary commodities, but many deposits may also contain Co, Ni, Bi, and In as coproducts or byproducts that can be refined from primary base- and precious-metal ores (Mudd et al., 2013). Abundant in British Columbia, skarns include several deposit subtypes, including Cu, Zn-Pb, W-Sn, Au-Ag, and Fe varieties (Ray et al., 1995; Ray, 2013). Cobalt, a critical component of low-carbon technologies, is most commonly enriched in the iron skarn subtype (Mudd et al., 2013), and numerous iron skarns, including several past-producing mines, are known from Vancouver Island, Texada Island, and the southern portion of Haida Gwaii (Hancock, 1988; Ray, 2013). Although these skarns have mainly been of interest for Fe, Cu, Au, and Ag, they are the most abundant hosts of Co mineralization in Wrangel terrane.

The Merry Widow deposit (Figs. 1, 2; also referred to as the Empire mine) is one of the largest past-producing iron skarns on Vancouver Island. It has a historical resource (cited in Giroux and Raven, 2008) that includes Co (0.013%) and Fe (16.1%) and, being actively explored, has a recent NI 43-101-compliant Measured and Indicated resource of 594,019 tonnes at 3.515 g/t Au and 0.505% Cu (Bird, 2023). Recent exploration at the Merry Widow deposit reports Co mineralization with concentrations up to 1 wt% associated with Au grades of 3.37 g/t in magnetite and sulphide ores (Northcote, 2023). This highlights the potential for byproduct Co from iron skarns in Wrangel terrane. Herein, we describe the geology of the Merry Widow deposit, and report preliminary field observations gathered as a part of an ongoing project focussing on characterizing critical mineral occurrences in British Columbia (Hickin et al., 2023; 2024).

2. Skarns and iron skarns

Skarns are characterized by garnet-rich calc-silicate alteration that is typically developed along contacts between intermediate to felsic intrusions and carbonate sedimentary rocks (e.g., Meinert et al., 2005). The classic model for base-metal skarn formation involves four main processes: 1) exsolution of metal-rich, SiO_2-charged hydrothermal fluids (i.e., magmatic-hydrothermal fluids) from a crystallizing melt and outward flux of these fluids into carbonate sedimentary host rocks; 2) initial thermal recrystallization of carbonate sedimentary host rocks and subsequent driving off of CO_3^{2-} from Ca-Mg-bearing carbonate rock and its replacement with hydrothermal SiO_2 (i.e., CO_3^{2-} loss and SiO_2 addition) to form calc-silicate alteration; 3) coincident precipitation of sulphide and oxide minerals in response to fluctuations in pressure, temperature,

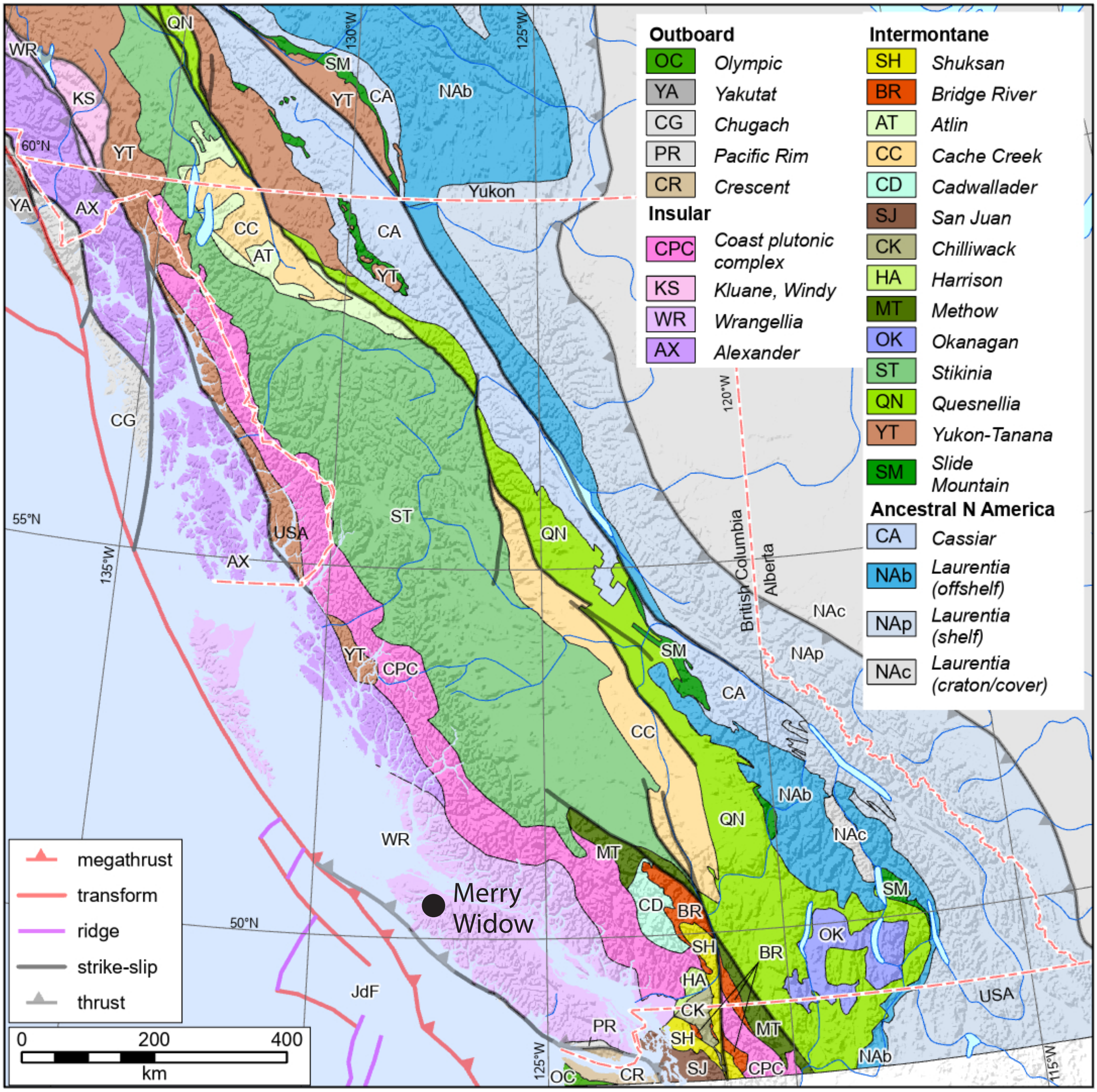

Fig. 1. Location of the Merry Widow deposit. Terranes modified from Colpron (2020).

and pH; and 4) collapse of the hydrothermal system and the inward flux of low-temperature aqueous fluids from external sources (Meinert et al., 2005). This series of processes forms a mineralized aureole of massive, anhydrous garnets, pyroxenes, and pyroxenoids (e.g., wollastonite) overprinted by secondary amphiboles, epidotes, and other volatile-bearing minerals along the interface between the causative intrusion and carbonate host rocks. Essential support for this model includes the observed spatial relationship between causative intrusions, carbonate host rocks, and calc-silicate alteration, the SiO_2-rich composition of high-temperature magmatic-hydrothermal fluids (Audétat, 2019), and the occurrence of abundant quartz veins that crosscut calc-silicate alteration in many skarn deposits.

Along with enrichment in Co, iron skarns are distinct from other skarn varieties (Einaudi et al., 1981; Dawson and Kirkham, 1996; Megaw, 1998). Key distinctions include: 1) they are commonly associated with gabbroic intrusions in space and time (Meinert et al., 2005); 2) they host massive low-Ti and low-V magnetite (Ray and Webster, 2007), and contain minor amounts of massive sulphide mineralization (pyrite-pyrrhotite-marcasite-chalcopyrite-arsenopyrite; Ray et al., 1996); 3) they

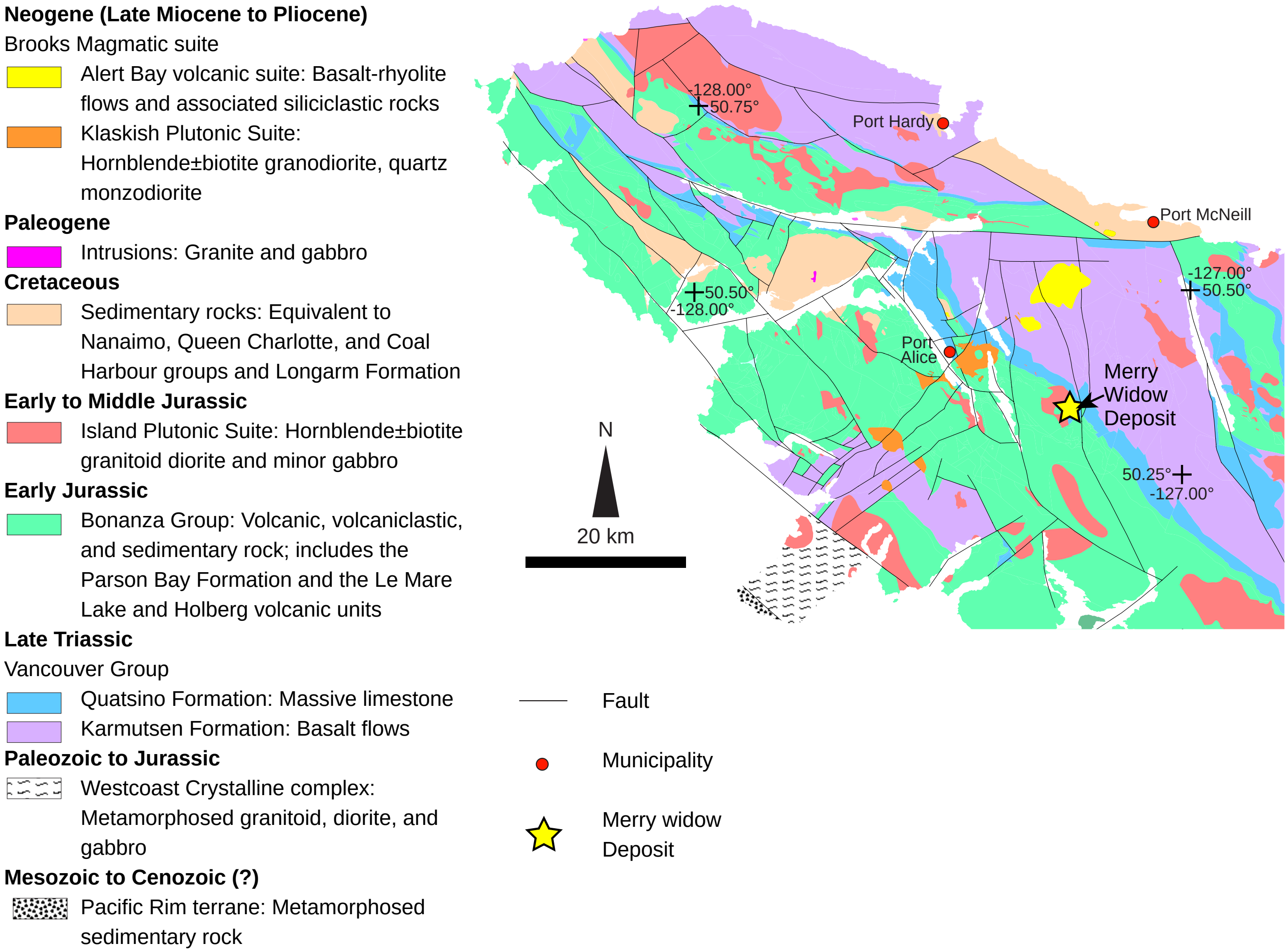

Fig. 2. Regional geology of northern Vancouver Island. Modified from Nixon et al. (2020).

contain Fe-rich calc-silicate alteration, and typically have abundant secondary albite and scapolite (Meinert et al., 2005); and 4) they tend to lack hydrothermal quartz (Meinert et al., 2005). These distinguishing features likely relate to distinct genetic processes by which iron skarns form and which drive their enrichment in critical metals.

2. Geological setting

Skarns on Vancouver Island, Texada Island, and Haida Gwaii share a common geologic setting and are formed along the interface between Jurassic intrusions, carbonate sedimentary rocks, and arc volcanic rocks. Vancouver Island is underlain by Paleozoic-Mesozoic rocks of Wrangel terrane which, together with Alexander terrane to the north, form Insular superterrane (Fig. 1). Basement rocks on northern Vancouver Island include Paleozoic island-arc volcanic and sedimentary rocks of the Sicker and Buttle Lake groups (Massey, 1995a-c). These rocks are overlain by the Vancouver Group (Upper Triassic), which comprises volcanic rocks of the Karmutsen Formation and carbonate sedimentary rocks of the Quatsino Formation (Nixon and Orr, 2007). Overlying the Vancouver Group is the Bonanza Group (Upper Triassic to Middle Jurassic; DeBari et al., 1999; Nixon and Orr, 2007), which includes an array of siliciclastic and carbonate sedimentary rocks and arc-related volcanic and volcaniclastic rocks (Bonanza arc). Major units of the Bonanza Group near the Merry Widow deposit include the Parson Bay Formation (Upper Triassic) and the Le Mare Lake volcanic unit (Lower Jurassic; Nixon et al., 2011a-d). Deposition of the Bonanza Group rocks was contemporaneous with the emplacement of gabbroic to granodioritic intrusions of the Westcoast Crystalline complex (ca. 190-174 Ma; DeBari et al., 1999; Canil et al., 2010) and diorite to granite intrusions of the Island Plutonic suite (ca. 201-166 Ma; Nixon et al., 2011a-d).

Intrusions of the Island Plutonic suite were emplaced at depths of 2-10 km and, in some areas, are overlain by volcanic rocks of the Bonanza Group (Canil et al., 2010). Bonanza Group rocks are overlain by, or are in fault contact with, the Coal Harbor Group, Longarm Formation (Lower Cretaceous), and Queen Charlotte and Nanaimo groups (Upper Cretaceous). Following deposition, the entire package of Paleozoic-Mesozoic rocks was folded into a broad antiform (Cowichan and Buttle Lake anticlinoria) that runs the length of Vancouver Island (Yorath et al., 1985; Canil et al., 2010).

3. Geology of the Merry Widow deposit

The Merry Widow deposit consists of several discrete magnetite-rich skarns along the northeast flank of Merry Widow Mountain (50.339252 °N, -127.284571 °W) in north-central Vancouver Island, ~17.5 km southeast of Port Alice (Fig. 2). Volcanic rocks of the Karmutsen Formation, the oldest rocks in the area (Fig. 3), are green-black, fine-grained, locally plagioclase phyric and contain abundant epidote- and carbonate-filled amygdules. Overlying the Karmutsen Formation along a variably brecciated contact is a >1 km thick sequence of carbonate sedimentary rocks assigned to the Quatsino Formation (Quatsino limestone; Ray and Webster, 1991). North of Merry Widow Mountain, this unit is dull gray and consistently strikes east-west and dips southward. Quatsino limestone immediately adjacent to the Merry Widow and Kingfisher pits (Fig. 3) has been significantly recrystallized (Ray and Webster, 1991). Along the northern end of the study area, the Quatsino limestone appears to grade upwards into a package of thinly bedded lithic tuffs and polymictic breccias containing abundant clasts of volcanic and plutonic rocks (Fig. 3). To the south, the upper contact of the Quatsino limestone is overlain by massive to thinly bedded tuff and volcaniclastic rocks (Fig. 3). In both cases, this upper unit is interpreted as the Parson Bay Formation, indicating that the contact between the Vancouver and Bonanza groups is conformable in this area (Fig 3; Nixon and Orr, 2007; Nixon et al., 2011d).

The oldest intrusive rocks in the area are fine- to coarse-grained, intermediate to mafic rocks of the Keystone intrusions, which Ray and Webster (1991) interpreted to be coeval with, and feeders to, Bonanza arc volcanic rocks. The Keystone intrusions include abundant ~65°northeast-dipping dikes and xenolith-bearing pipes emplaced into Quatsino limestone (Ray and Webster, 1991; Nixon et al., 2011d). Keystone intrusive rocks are variably altered, with some outcrops being fresh igneous rocks and others being completely converted to chlorite-rich, calc-silicate assemblages.

The Coast Copper intrusion (also referred to as the Merry Widow pluton) is the youngest intrusion in the Merry Widow area. This intrusion is part of the Island Plutonic suite and ranges from varitextured gabbro around its periphery (~197.4 ± 0.5 Ma; Nixon et al., 2011d) to coarse-grained quartz monzonite in its interior (~197.1 ± 0.3 Ma; Nixon et al., 2011d). At the surface, the intrusion is bordered to the east by the Parson Bay Formation and at depth, as reported from the Benson Lake mine (Travis et al., 2022), is in contact with highly deformed carbonate sedimentary rock of the Quatsino Formation (Fig. 3).

North- and northeast-striking faults crosscut the Merry Widow area (Figs. 2,3). The north-striking faults are the oldest and include the Merry Widow fault, which splays off a larger north-striking fault to the south (Benson River fault of Lund, 1966). The northeast-striking faults are younger and include the Kingfisher, Marten, and Raven faults. This latter group displays only minor apparent strike-slip offset and was interpreted as a significant control on the distribution of magnetite and sulphide mineralization at Merry Widow by Eastwood (1965) and Lund (1966).

5. Mineralization, textures, and alteration at the Merry Widow deposit

The Merry Widow deposit (Fig. 3, Table 1) includes several sulphide-bearing magnetite orebodies previously developed as open pits (Merry Widow, Kingfisher, and Raven), and underground workings (Old Sport horizon), and abundant Cu-, Au-, and Co-bearing massive sulphide occurrences (Copper Knob, Marten, Snowline, Blue Bird, Dry Hill, and North Notch; Ray and Webster, 1991; Bird, 2023).

5.1. Merry Widow, Kingfisher, and Raven ore bodies

The Merry Widow, Kingfisher, and Raven orebodies form a cluster of structurally controlled magnetite-calcite orebodies that were developed as open pits. From 1957 to 1967, the pits were mined primarily for Fe from relatively pure magnetite-calcite orebodies. During production, sulphides were avoided or discarded as waste rock (Travis et al., 2022). At their closing, production from these orebodies totalled ~1.68 Mt of ore (Bird, 2023).

The Merry Widow orebody is centred on the Kingfisher fault and consists of a single lenticular magnetite-calcite mass with minor massive to disseminated sulphides (Fig. 4; Eastwood, 1965). The magnetite-calcite mass is ~3,500 m^2 in 2D cross-section and has a ~200 m diameter surface area (estimate based on Lund, 1966; Ray and Webster, 1991; Fig. 3b). The sulphides are mostly pyrite-chalcopyrite-pyrrhotite, with minor marcasite, cobaltite, and Co-bearing arsenopyrite. Contact relationships in the Merry Widow orebody are complex. Most of the orebody is hosted in the Parson Bay Formation but it is also in contact with a mass of Keystone intrusion along its northern margin and the Island Plutonic suite to the west (Fig. 3). Phlogopite in the skarn alteration in the Merry Widow orebody has a K/Ar date of 197.9 ± 1.3 Ma (Nixon et al., 2000), indicating that the orebody formed contemporaneously with emplacement of the Coast Copper intrusion.

The mineralogy and morphology of the Raven orebody is like the Merry Widow orebody. However, the orebody is smaller and hosted entirely in the Parson Bay Formation along the Raven fault (Fig. 3). This orebody was mined out early in the development of the Merry Widow deposit and was subsequently backfilled with tailings (Travis et al., 2022).

The Kingfisher orebody consists of two pipe-like masses of relatively pure magnetite-calcite ore, <50 m in diameter, with minimal associated calc-silicates or sulphides (Eastwood, 1965). The two masses are entirely within Quatsino Formation limestones along the Kingfisher fault (Eastwood, 1965). At depth, the two pipe-like bodies join and continue downward for an unknown distance (Fig. 3b; Lund, 1966).

5.1.1. Magnetite ore textures

Magnetite in the Merry Widow and Kingfisher orebodies ranges from coarse to fine grained but typically includes abundant euhedral magnetite crystals up to 1 cm wide. Magnetite in these orebodies also occurs in a variety of distinctive textural styles, including nodular colloform magnetite masses, aggregates of radiating, lath-like magnetite crystals (described by Stevenson and Jeffery, 1964; Lund, 1966; Haug, 1976), planar masses of magnetite surrounded by euhedral calcite (i.e., banded magnetite-calcite ores), and tabular magnetite-calcite masses that crosscut host rock stratigraphy along sharp contacts.

Banded magnetite-calcite ores (Fig. 5) are the most common textural variety in the Merry Widow and Kingfisher orebodies. The magnetite bands consist of planar masses that range

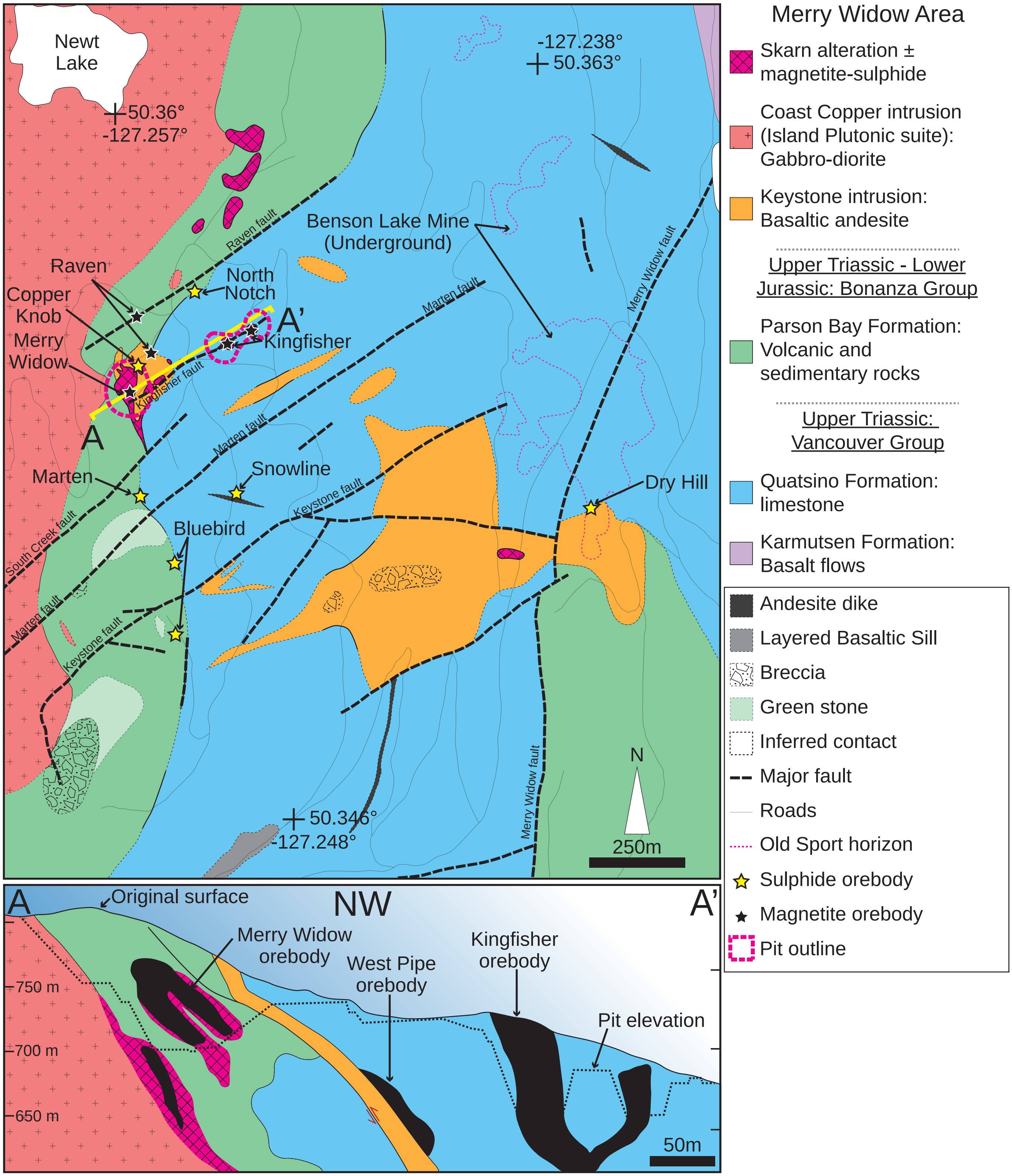

Fig. 3. a) Geology of the Merry Widow deposit area. Modified from Ray and Webster (1991) with observations from this study. **b)** Schematic cross section through the Merry Widow and Kingfisher pits. Adapted from Lund (1966) and Ray and Webster (1991) based on work from this study.

Table. 1. Mineralization at the Merry Widow deposit.

Occurrence	Description	Host	Texture	Reported mineralization*
Merry Widow	Massive magnetite-calcite orebody along the western end of the Kingfisher fault. Primarily magnetite with variable pyrrhotite-chalcopyrite-pyrite and minor cobaltite and Co-bearing arsenopyrite. Calc-silicate alteration primarily in igneous host rocks.	Parson Bay Formation and Keystone intrusion	Massive with abundant euhedral magnetite	Fe, Cu, Au, Ag Co, As, Zn
Kingfisher	Massive magnetite-calcite orebody along the eastern end of the Kingfisher fault. Primarily magnetite with minor sulphide mineralization and calc-silicate alteration.	Quatsino Formation limestone	Massive with abundant euhedral magnetite	Fe, Cu, Co
Raven	Massive magnetite-calcite orebody along the western end of the Raven fault. Primarily magnetite with minor pyrrhotite-chalcopyrite-pyrite.	Parson Bay Formation	Massive with abundant euhedral magnetite	Fe, Cu, Au, Ag, Co, Zn
Old Sport horizon (Benson Lake and Old Sport mines)	Massive magnetite orebody pervasively overprinted by secondary chalcopyrite-bornite-pyrrhotite and minor cobaltite, and Co-bearing arsenopyrite. Calc-silicate alteration is pervasive in and around the orebody.	Contact between Karmutsen Formation and Quatsino Formation limestone	Massive with discontinuous magnetite lenses and veins	Fe, Cu, Ag, Au, Co
Copper Knob	Sulphide occurrence consisting of weathered masses of pyrrhotite-pyrite-chalcopyrite-arsenopyrite-marcasite, Fe-rich gossan, and euhedral calcite centered around a mafic dike.	Quatsino Formation limestone	Massive	Cu, Au, Co, As
Marten	Sulphide occurrence consisting of weathered masses of pyrrhotite-pyrite-chalcopyrite-arsenopyrite-marcasite, Fe-rich gossan, and euhedral calcite centered around a mafic dike.	Quatsino Formation limestone	Massive	Fe, Cu, Au, Co, As, Zn
Bluebird	Sulphide occurrence	Quatsino Formation limestone	Massive	Fe, Cu, Au, Zn
Snowline	Sulphide occurrence	Quatsino Formation limestone	Massive	Fe, Cu, Au
North Notch	Sulphide occurrence	Quatsino Formation limestone	Massive	Fe, Cu, Au, Ag Co
Dry Hill	Sulphide occurrence	Quatsino Formation limestone	Massive	Cu, Co

*Modified from Ray and Webster, 1991

Fig. 4. Massive magnetite ore bodies in volcanic host rocks, Merry Widow pit.

in thickness from 2 to >10 cm and display a zonation with interiors consisting mainly of randomly oriented, fine-grained crystals that grade outward to margins consisting of coarse-grained, euhedral crystals (Fig. 5). Extending outward from the euhedral magnetite substrate are euhedral actinolite and quartz crystals orientated with their c-axes at medium to high angles to the planar magnetite substrate (Fig. 5d). The actinolite and quartz are surrounded by massive, sulphide-bearing, euhedral calcite that form the interstitial material between planar masses of magnetite.

The abundance of euhedral calcite in the banded magnetite-calcite ores varies along the vertical extent of the Merry Widow and Kingfisher orebodies. In the Kingfisher adit, below the Merry Widow and Kingfisher pits, ores contain ~ 30-50 vol. % calcite. At shallower levels, the calcite layers are thinner, constitute <5% by volume, and the surfaces of euhedral magnetite appear stacked on top of one another, with a thin layer of interstitial calcite. Where the calcite has weathered out of the interstitial space, the resulting void appears planar and is lined with euhedral magnetite resembling a crystal-lined vug. Previous work on the Merry Widow orebody and other iron skarn deposits on Vancouver Island have classified these features as magnetite druses (e.g., Eastwood, 1965).

Tabular magnetite-calcite ores observed below the Kingfisher and Merry Widow pits, are 0.05 to 1 m wide, have lozenge-like shapes, crosscut host rocks along sharp contacts (Fig. 6), and appear planar when observed crosscutting the parallel walls of the Kingfisher adit. These ores contain calcite-sulphide-actinolite-quartz masses within their interiors (Fig. 6c).

5.1.2. Sulphide-bearing calcite and magnetite

Pyrite-pyrrhotite-marcasite-chalcopyrite-arsenopyrite masses occur throughout the Merry Widow and Kingfisher orebodies and are the most common host for minor cobaltite and Co-bearing arsenopyrite minerals (Fig. 7). These sulphide masses are generally in contact with masses of carbonate

Fig. 5. a) Banded magnetite-calcite ore along a wall in the Kingfisher adit. **b)** Close-up of the area outlined in white in a); magnetite layers are zoned, with coarse-grained euhedral magnetite margins and fine-grained interiors (dashed white lines). **c)** Euhedral magnetite from the coarse-grained margin of a planar magnetite band. **d)** Schematic cartoon of banded magnetite-calcite ore. Note that the actinolite and quartz extend at moderate to high angles from the magnetite substrate.

minerals that commonly consist of course (2 to >18 cm) euhedral calcite. Sulphides are rarely seen intergrown with magnetite in the absence of carbonate. Sulphide-bearing calcite is observed in a variety of contexts in the magnetite orebodies, including >1 m-thick envelopes that surround magnetite orebodies along their peripheries, rounded masses within massive magnetite orebodies, and interstitial to banded and tabular magnetite-calcite ores (Fig. 6c).

5.1.3. Breccias and alteration

Breccias at the periphery of the Merry Widow orebody typically surround the edges of the massive magnetite-calcite ores and include magnetite breccias with a calcite-quartz matrix (Fig. 8a) and zones of highly altered, fragmentary volcanic rocks in a pale-green, fine-grained, albite- and carbonate-rich matrix that vigorously fizzes in the presence of hydrochloric acid (Figs. 8b-f). Many of the volcanic rock fragments display carbonate-rich sodic alteration rinds surrounding remnant cores (Fig. 8b-f). In some cases, the modal abundance of matrix material in these breccias is up to ~50 vol. %. Aureoles of recrystallized Quatsino Formation limestones extend outward from the margins of Coast Copper intrusive rocks (Fig. 9). Close to the

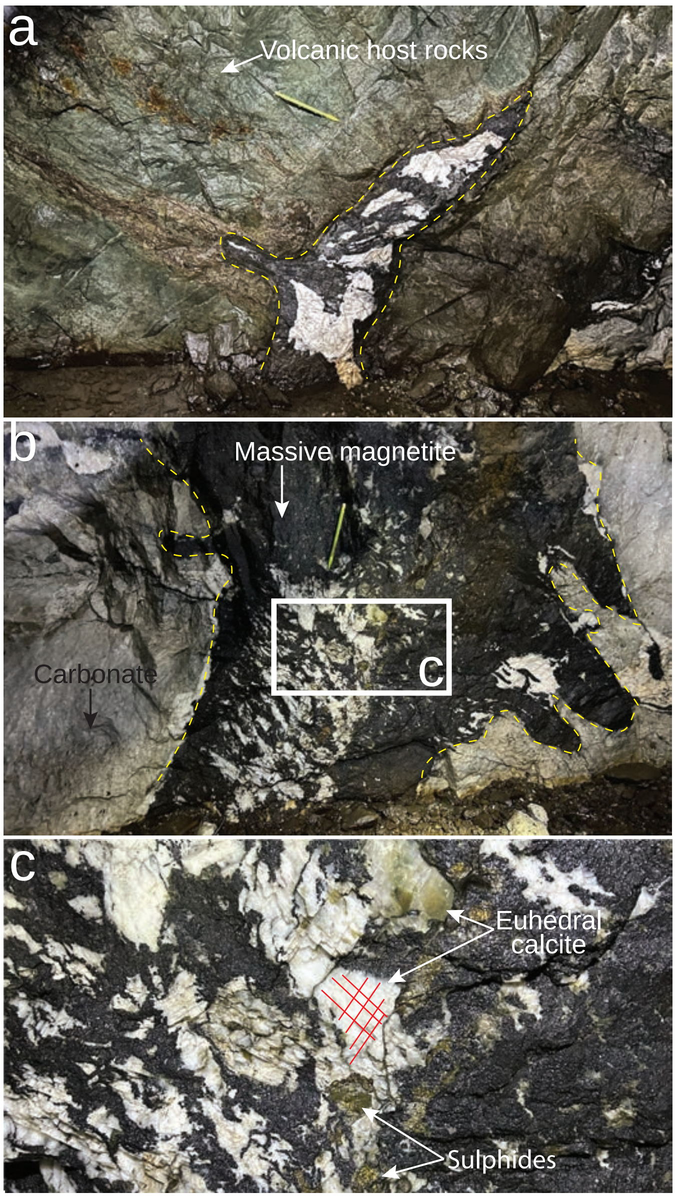

Fig. 6. a) Tabular magnetite-calcite ore crosscutting volcanic rock. **b)** Tabular magnetite-calcite ore crosscutting carbonate rock, with sharp, sinuous contacts (outlined in yellow). **c).** Close-up of area in b) showing calcite-sulphide-actinolite-quartz masses isolated within magnetite.

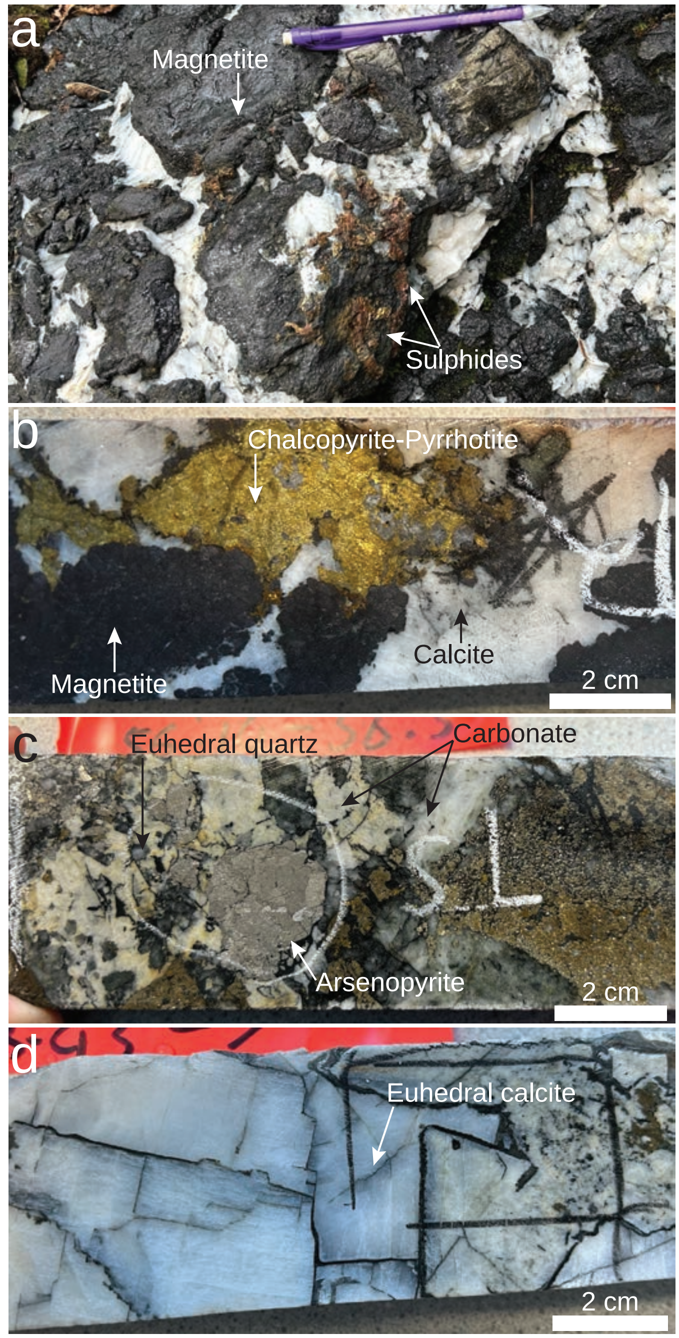

Fig. 7. Sulphide and magnetite-calcite ore at the Merry Widow ore body. **a)** Chalcopyrite and pyrrhotite magnetite-calcite ore along the edge of the Merry Widow orebody. **b)** Sulphide-bearing massive calcite in magnetite-calcite ore in drill core. **c)** Carbonate and euhedral quartz surrounding aggregates of sulphide in drill core. **d)** Massive euhedral calcite like that surrounding massive magnetite ore zones.

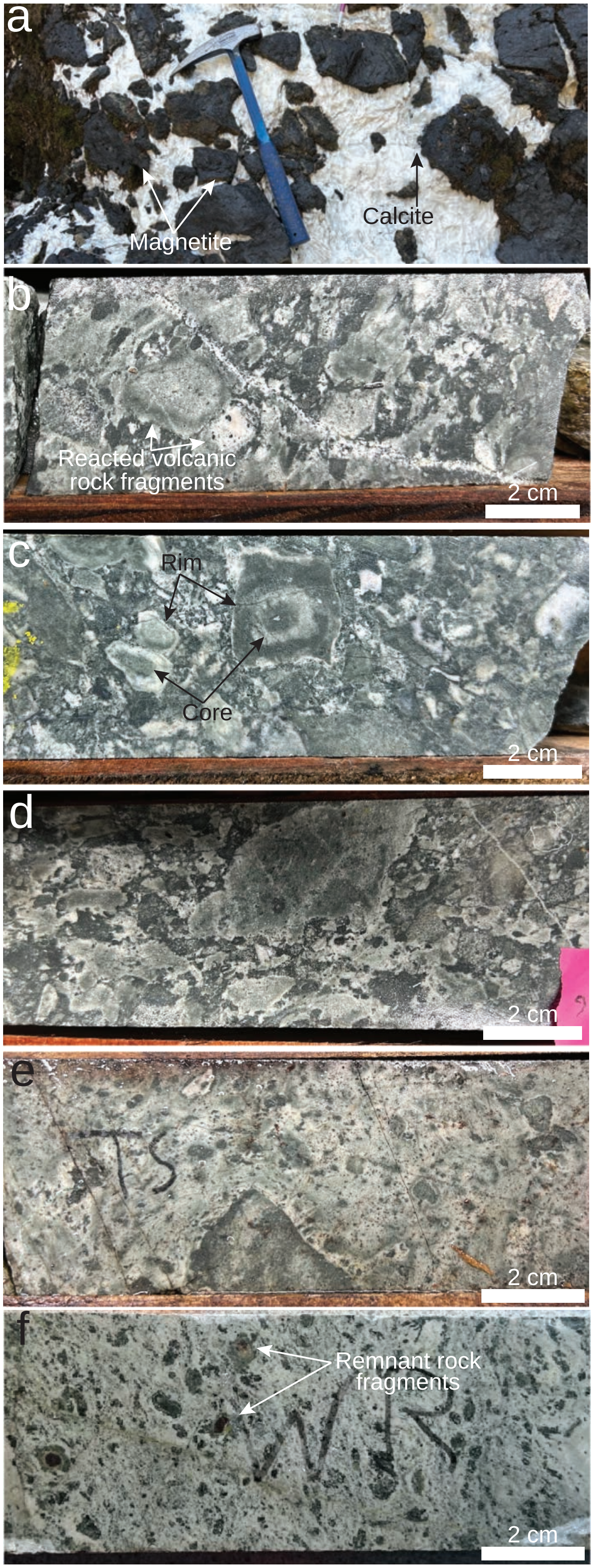

Fig. 8. a) Magnetite breccia with coarse-grained, euhedral calcite cement. **b-f)** Altered volcanic rock fragments in carbonate and albite-rich matrix. From b) to f), the rock fragments become progressively more bleached along their edges as the volume of matrix material increases. Note the rims around the breccia fragment in b) and c), the serrated, patchy boundaries of the rock fragments in d), and the corresponding modal increase in matrix material. In e) and f), the rock fragments are also surrounded by halos, and most of the samples consist of matrix material.

intrusive rocks, recrystallization is intense, and the limestones have been converted to masses, of course, mm- to cm-scale calcite crystals whereas farther away, recrystallization is less intense and primary sedimentary structures are preserved.

Calc-silicate alteration at the Merry Widow deposit consists mainly of masses of euhedral, coarse-grained andradite, grossular garnet (Ettlinger and Ray, 1989), and epidote, with variable amounts of actinolite. These zones of alteration do not contain significant oxide or sulphide mineralization. In contrast to base-metal skarn deposits elsewhere, calc-silicate alteration in the Merry Widow deposit is most widespread in igneous host rocks and is only observed in minor volumes in carbonate host rocks immediately adjacent to intrusions (Morris and Canil, 2022). The contrast in the abundance of calc-silicate alteration between carbonate- and silica-rich rock types is particularly apparent along the margins of many of the mafic dikes that crosscut recrystallized Quatsino Formation limestone in the Kingfisher adit. Here, calc-silicates are abundant in the mafic dikes and commonly absent in adjacent limestones (Fig. 10a). In this example, the calc-silicate alteration appears to spread away from limestones into the dikes along carbonate-filled fractures lined with calc-silicates formed in the adjacent mafic host rock. A similar relationship is observed where tabular magnetite-calcite ores crosscut igneous host rocks. In this context, calc-silicate alteration is developed in igneous host rocks, surrounds the tabular ore body, and appears to extend outward from it (Fig. 10b). Also, in contrast to base-metal skarns elsewhere (Meinert et al., 2005), quartz veins or other

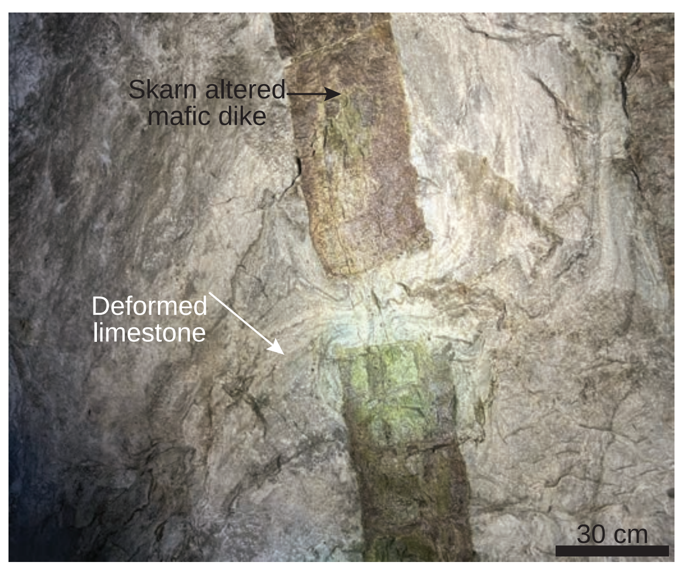

Fig. 9. Boudin of epidote- and garnet-altered mafic dike surrounded by deformed and recrystallized limestone ~550m from the Coast Copper intrusion.

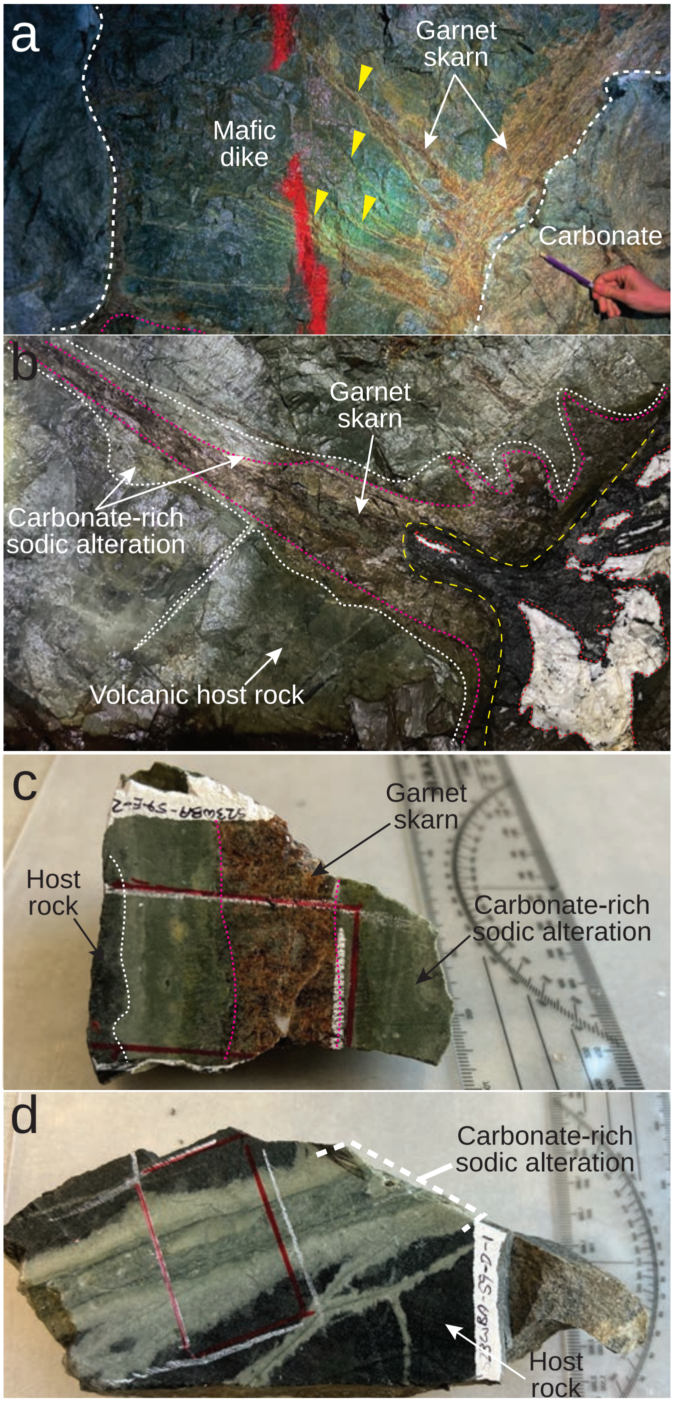

Fig. 10. a) Skarn alteration at the contact between a mafic dike and unaltered carbonate host rocks (defined by dotted white line) at the Kingfisher adit. A 10 cm-wide zone of garnet skarn alteration in the mafic dike continues along the contact. Extending at high angles away from this zone are garnet skarn alteration and carbonate-filled veinlets tapering into the dike (yellow arrows). **b)** Skarn alteration in volcanic host rocks in contact with a tabular magnetite-calcite body (outlined in yellow). Away from the volcanic rocks is a zone of carbonate-rich sodic alteration (outlined in white) that transitions to garnet alteration (outlined in pink). The geometry of these zones is roughly concordant with the geometry of the magnetite-calcite body. **c)** Central zone of garnet alteration (outlined in pink) bounded by zones of carbonate-rich sodic alteration in volcanic host rock. **d)** Veinlets of carbonate-rich sodic alteration in volcanic host rock.

silica-rich hydrothermal features are not abundant at Merry Widow and have not been observed in spatial association with calc-silicate alteration.

Zones of calc-silicate alteration in igneous host rocks are commonly surrounded by pale-green carbonate-rich sodic alteration haloes (Figs. 10c, d), referred to as bleaching in earlier works (e.g., Eastwood, 1965). This alteration is not typically texturally destructive (i.e. the primary igneous texture is preserved) and involves Na addition and Fe loss (Eastwood, 1965; Malek, 2021). The loss of Fe is apparent by the lack of magnetism of altered rocks that would otherwise be magnetic when fresh. Similarly, unbleached igneous host rocks typically do not effervesce, suggesting the development of carbonate minerals in host rocks during the development of this alteration type.

5.2. Old Sport horizon orebody

The Old Sport horizon is the largest magnetite orebody at the Merry Widow deposit. The horizon was mined via underground workings between 1962 and 1972 at the Benson Lake mine (Fig. 3) and the Old Sport mine, north of the study area. Most of the production was from the Benson Lake mine, which accounted for ~2,621,131 tonnes of ore with 41,192 tonnes of Cu, 377,165 oz of Ag, and 124,386 oz of Au from the sulphide mineralization.

The orebody follows a sill-like body of diorite that was emplaced along the westerly dipping (~40°) contact between Karmutsen Formation volcanic rocks and overlying Quatsino Formation limestones and consists of a 0.6 to 30 m-wide interval of variably brecciated, rock immediately surrounding a sill of diorite (Travis et al., 2022). Calc-silicate alteration is pervasive along the Old Sport horizon such that the host protolith (carbonaceous or tuffaceous rock) immediately adjacent to the magnetite orebody is unclear (Berkshire and Hume, 2019). Massive magnetite along the Old Sport horizon forms discontinuous lenses and veins and is overprinted by chalcopyrite, bornite, and pyrrhotite and minor marcasite, cobaltite, and Co-bearing arsenopyrite.

5.3. Marten, Copper Knob, Bluebird, Snowline, North Notch, and Dry Hill occurrences

The Marten, Copper Knob, Bluebird, Snowline, North Notch, and Dry Hill occurrences (Fig. 3; Table 1) consist of weathered masses of Cu-Au-bearing pyrite-pyrrhotite-marcasite-chalcopyrite-arsenopyrite, euhedral calcite, minor cobaltite, Fe-rich gossan, and sulphide gossan (Fig. 11). The occurrences commonly contain Co mineralization in the form of cobaltite, and Co- and As-bearing sulphides and arsenides (Ray and Webster, 1991). The sulphide mineral masses are relatively pure and are typically hosted in limestone close to the contact of the Quatsino and Parson Bay formations (Fig. 3) and have not been observed to crosscut massive magnetite orebodies. These occurrences are typically ~0.5-2 m wide and laterally continuous for several m. Previous work has described their morphology as planar or manto-like (e.g., Wilton, 1990). These occurrences have never been mined but are currently being prospected for sulphide-hosted Cu and Au mineralization (Travis et al., 2022).

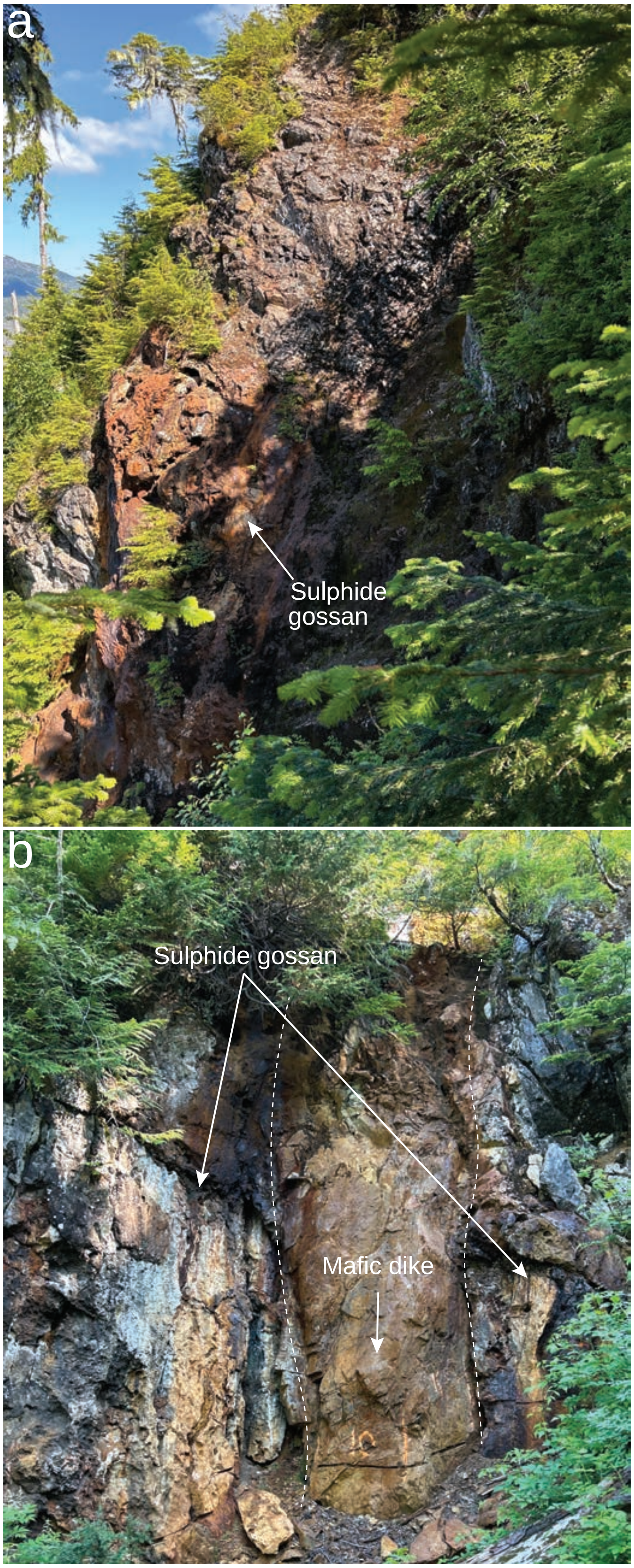

Fig. 11. a) Gossan in tabular massive sulphide mineralization. **b)** Sulphide gossans along the periphery of a near-vertical mafic dike (outlined in white).

At the Marten and Copper Knob occurrences, the sulphide masses are tabular bodies, 2-4 m wide, in recrystallized limestone adjacent to mafic dikes (Fig. 12). The dikes are strongly altered to albite, chlorite, and calc-silicate assemblages, have well-developed chilled margins (1 to >3 cm wide; Fig. 12), and contain euhedral calcite crystals in their interiors. The sulphide-bearing bands include discrete zones of magnetite-sulphide, calcite, and massive sulphide (Figs. 12a, b). The magnetite-sulphide zone is directly adjacent to the dike and ranges in thickness from 2 to >10 cm (Fig. 12a). The magnetite-sulphide zone grades outward into a 0.01 to >2 m-wide zone of massive, euhedral, coarsely crystalline calcite (2->18 cm; Fig. 12a). This calcite zone is typically tabular and monomineralic but can also include calcite lenses surrounded by euhedral actinolite and quartz (Fig. 13b), and sulphide-bearing calcite veins that crosscut recrystallized limestone (Fig. 12c). The outer edge of the calcite zone either has a sharp, well-defined contact with recrystallized carbonate sedimentary rock (Fig. 13b) or grades outward into massive sulphide (Fig. 13b). The outer massive sulphide zone ranges in width from 0.5 to >3 m (Fig. 11) and can extend 3 to >10 m along strike. Both Marten and Copper Knob are primarily pyrrhotite-chalcopyrite-pyrite, but sulphide mineralogy can vary between prospects, with some predominantly chalcopyrite-pyrite and others 30-40% arsenopyrite.

Most of the dikes and sills observed in this study have sulphide and magnetite mineralization, but the degree of mineralization appears random relative to age, composition, or orientation. For example, one set of dikes in outcrop (e.g., Marten and Copper Knob) contain massive sulphides, whereas other dikes with the same orientation, composition, and apparent age in the same area have very little sulphide. Dikes and sills with massive sulphide mineralization only occur in carbonate sedimentary rocks.

6. Discussion

The Merry Widow deposit is an example of a Co-bearing iron skarn deposit in Wrangel terrane. The deposit displays features similar to those that differentiate iron skarns from other base-metal skarn varieties (Einaudi et al., 1981; Megaw, 1998; Dawson and Kirkham, 1996). These differences include the spatial and temporal association with gabbroic intrusions, massive magnetite orebodies, abundant Fe-rich calc-silicate alteration, minor volumes of massive sulphide, and a paucity of hydrothermal quartz.

The paucity of quartz veins, which are generally abundant in hydrothermal systems, is inconsistent with the classic magmatic-hydrothermal skarn model. Other features at Merry Widow that contrast with those predicted by the classic model include: 1) calc-silicate alteration primarily in igneous host rocks that have greater SiO_2 contents than sedimentary carbonate hosts, and a corresponding paucity in the carbonate host rocks; and 2) the apparent association between calc-silicate alteration and carbonate-rich veins bounded by carbonate-bearing sodic alteration halos. Although the genetic significance of these features is unclear, veins and alteration are common pathways for mineralizing fluids and sites of fluid-rock reactions. Accordingly, alteration and mineralization at Merry Window likely involved mobilization of CO_3^{2-} and Na- and that fluid-rock reactions affected the composition of igneous hosts more

Fig. 12. a) Mafic dike with chilled margins (red lines),outer bands of magnetite (green lines, bounded by euhedral calcite (black lines) and massive sulphide. **b)** Mafic dike with chilled margins bounded by euhedral calcite and massive sulphide (Copper Knob). **c)** Edge of mafic dike showing marginal magnetite and a euhedral calcite zone with a segregated sulphide mass along its sharp contact with recrystallized carbonate host.

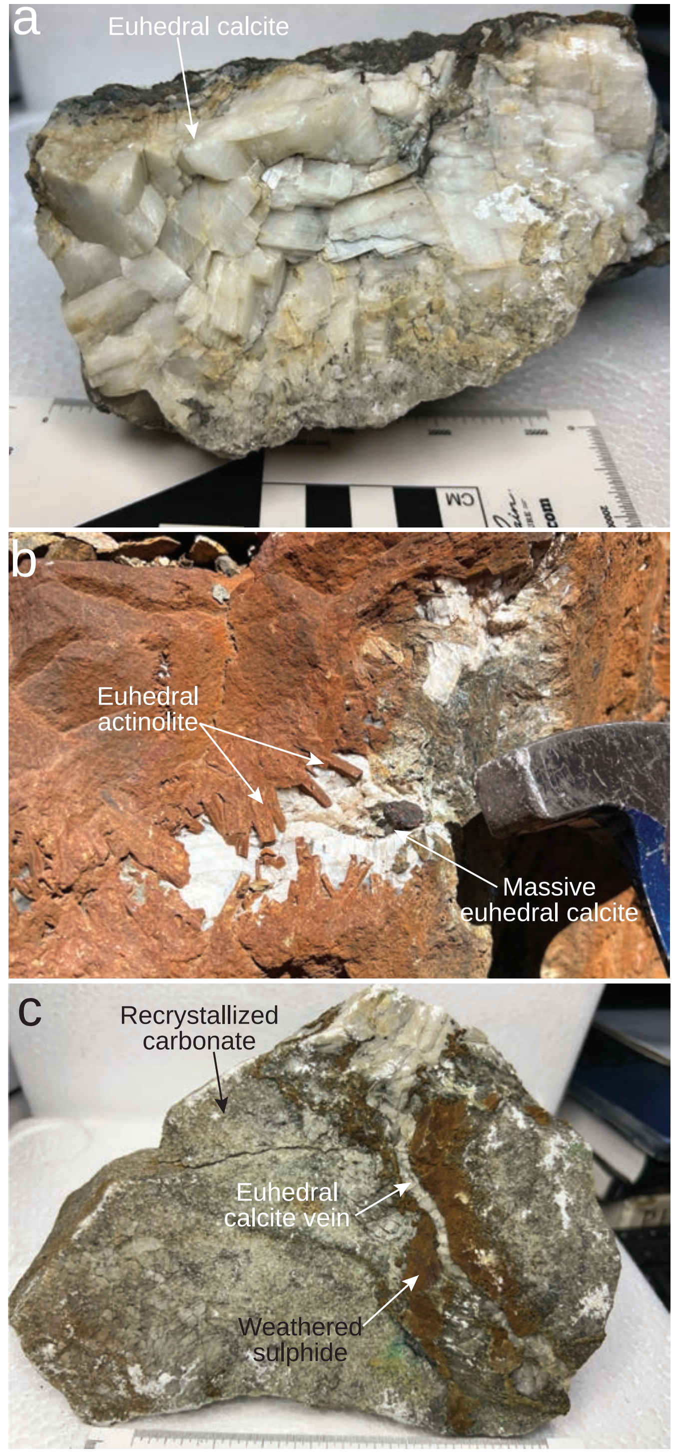

Fig. 13. a) Coarse-grained, euhedral calcite from the calcite zone adjacent to a mafic dike at the Copper Knob massive sulphide occurrence. **b)** Euhedral calcite lens surrounded by euhedral actinolite. **c)** Recrystallized limestone host with disseminated sulphide surrounding a veinlet with coarse-grained, euhedral calcite.

than carbonate sedimentary hosts.

The occurrence of carbonate-bearing sodic alteration and calc-silicate alteration of igneous rocks in the Merry Widow deposit is an unusual and conspicuous feature that differs from how calc-silicate and hydrothermal alteration occurs in most magmatic-hydrothermal deposit types. These features appear to have formed in parallel with and as a result of the processes that occurred during the formation of oxide- and Co-bearing sulphide mineralization in this deposit. The same is likely true for other Co-bearing iron skarn deposits on Vancouver Island. It follows then that identification of these features could serve as field indicators of possible Co-bearing sulphide mineralization at other skarn localities in British Columbia.

5. Conclusion

Iron skarns are important targets for critical mineral exploration. The Merry Widow deposit is an example of a Co-bearing iron skarn in Wrangel terrane and contains host-rock alteration and mineralization features that deviate from that predicted by the conventional skarn model. Among these are the apparent lack of quartz veins associated with mineralization and alteration and the development of carbonate-rich sodic and calc-silicate alteration predominantly in igneous rocks rather than in carbonate sedimentary rocks. Although the genesis of these features is unclear, their distinction from the characteristic features of other skarn varieties and their identification can be used to characterize Co-bearing iron skarns like Merry Widow in the field.

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