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Volcanogenic massive sulphide (VMS) deposits in British Columbia: A review

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Front cover: Clastic ore grading 415 g/t Au and 14,000 g/t Ag. Poorly sorted ore clasts consist of fine grained sulphides and sulphosalts. From the 21B zone, Eskay Creek mine, Stikine terrane, northwestern British Columbia.

Back cover: Pyritic mudrocks and rhyolite flows, capped by basalt flows, Eskay rift, (upper Hazelton Group, Iskut River Formation on 'pillow basalt ridge'), Stikine terrane, northwestern British Columbia.

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Abstract
Volcanogenic massive sulphides (VMS) are syngenetic metal sulphide deposits precipitated near submarine hydrothermal vents discharging waters heated by volcanism. Approximately 600 mineral occurrences in British Columbia have characteristics of VMS deposits. These deposits formed in relatively narrow stratigraphic intervals during spans of intense volcanic activity, producing clusters in time and space. Although globally, VMS deposits started forming in the Archean and continue forming today, the British Columbia deposits range from Cambrian to Cretaceous. Paleozoic deposits are the most numerous, but the two largest known deposits (Britannia and Windy Craggy) are Mesozoic, and Mesozoic rocks host the most ore delineated to date and include ore of the highest value. Using the most recent British Columbia Geological Survey mineral deposit profile scheme for base and precious metals-bearing marine volcanic associated deposits (Besshi, G04; Cyprus, G05; Kuroko, G06; hybrid G07; and Noranda, G08), Kuroko deposits are by far the most common. Notable examples are in Wrangell terrane (Sicker Group), Stikine terrane (Kutcho assemblage, Eagle Bay assemblage, Stikine assemblage and Hazelton Group) and in post-accretionary overlap assemblage rocks (Gambier Group). Parts of these terranes and the Yukon-Tanana terrane are prospective but underexplored. Hybrid precious metals enriched deposits are well documented in upper Hazelton Group rocks, but probably also occur in the Eagle Bay assemblage, where several deposits are also highly enriched in precious metals, particularly silver. Besshi deposits are represented in the Lardeau Group of Ancestral North America, the Stuhini Group of Stikine terrane, and the Tats Group of Alexander terrane. Less well-recognized are those of the southern Quesnel and southern Alexander terranes. Cyprus deposits are relatively uncommon, but examples occur in Slide Mountain, Cache Creek and Bridge River terranes. Deposits of the Anyox camp at the southern end of the Eskay Rift are in a pendant of Hazelton Group basalts and interpreted as Cyprus type. VMS deposits may be of interest not only for base metals, but for precious metals and other metals on Canada's critical minerals list. Although favourable lithological associations are commonly recognized in the province, the relatively restricted geometry of VMS deposits pose exploration challenges. Consequently, some areas have seen relatively little recent exploration and may represent overlooked opportunities.

Keywords: volcanogenic massive sulphide, VMS, tectonic setting, northern Cordillera, mineral deposits, deposit models, deposit profiles, Kuroko, Besshi, Cyprus, hybrid VMS

1. Introduction

Volcanogenic massive sulphide (VMS) or volcanic-hosted massive sulphide (VHMS) deposits are syngenetic metal sulphide accumulations precipitated near submarine hydrothermal vents that discharge waters heated by volcanism. In British Columbia, VMS deposits are historically important sources of base and precious metals (Fig. 1). In addition to zinc, copper, lead, silver, and gold, these deposits may contain by-products such as cobalt, manganese, and nickel, which are needed for the ongoing shift away from fossil fuel-based energy. The British Columbia Geological Survey MINFILE database records approximately 600 VMS occurrences distributed in at least 10 areas of the province that have significant potential. Given the importance of VMS deposits as sources of the critical metals needed for a low-carbon economy, this paper is intended to update a previous summary by Massey (1999) and draw renewed attention to the deposit type.

The Cordilleran orogen represents a collage of accreted allochthonous terranes, parautochthonous terranes, and autochthonous basement (Fig. 2). Because metallogeny is so intimately tied to tectonic evolution (e.g., Nelson et al., 2013a, Colpron and Nelson, 2021) the treatment below considers VMS deposits in the context of Cordilleran terranes.

2. Past production and current exploration

Since 1898, 42 VMS deposits in British Columbia have produced 125.6 Mt of ore for 5.4 Moz Au, 253 Moz Ag, 1.57 Mt Cu, 111,000 t Pb, and 1.66 Mt Zn (Fig.1). Most production has come from a handful of operations. The top four deposits, by tonnes of ore mined, are: 1) Britannia (47 Mt produced 517,000 t Cu, 125,000 t Zn, 5.8 Moz Ag, 494,000 oz Au); 2) Myra Falls (combined production of more than 30 Mt for 424,321 t Cu, 1,458,720 t Zn, 71,630 t Pb, 35,697,000 oz Ag, 1,160,000 oz Au); 3) Anyox (Hidden Creek 22 Mt for 321,546 t Cu, 6.6 Moz

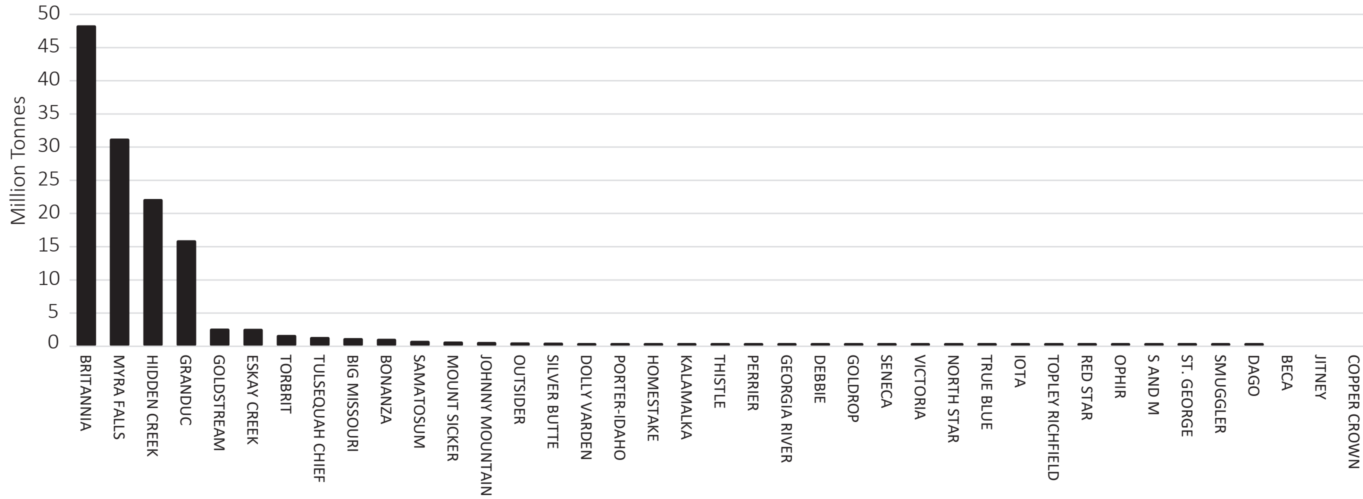

Fig. 1. Tonnes mined from VMS deposits 1898-2020.

Ag, 121,297 oz Au); and 4) Granduc (16 Mt for 190,144 t Cu, 64,303 oz Au, 3,990,000 oz Ag). Although no new producers have begun operation since 1999, Eskay Creek continued to produce until 2007 and Myra Falls resumed production in 2019 after a three-year hiatus.

Currently, Kutcho Creek and Yellowhead are at the feasibility stage of development, and Eskay Creek is now an advanced exploration project at the preliminary feasibility stage (see Clarke et al., 2022). Yellowhead, a remobilized VMS deposit, is a proposed bulk tonnage open-pit operation. Eskay Creek is an atypical example of a VMS deposit because of its enrichment in precious metals (see Galley et al. 2007), and its economic importance is not reflected by the measure of tonnes originally mined. It was a high-grade, high-value mine, even during a period of relatively low precious metals prices. From 1996 to 2007, 2.2 Mt of ore produced 159 million ounces of silver and 3.3 million ounces of gold.

3. Geology

VMS deposits are mainly stratiform, locally mound-shaped and, in some cases, structurally controlled. Some degree of post-depositional remobilization is common (e.g., Marshall et al., 2000). They typically form at or near the sea floor at water depths of 700 to 2000 m (Monecke et al., 2014) in extensional environments with thin crust, intense volcanism, and high heat flow, such as in back arc basins, intra-arc rifts, incipient rifts, forearc basins, and mid-ocean ridges. The deposits are commonly polymetallic, with characteristic base metal zonation. For comprehensive reviews describing VMS and considering their origins see Lydon (1984; 1988) Franklin et al. (2005), Galley et al. (2007), Piercey (2011), and Ross and Mercier-Langevin (2014).

3. 1. Temporal and spatial distribution

VMS deposits tend to form within relatively narrow stratigraphic intervals during spans of intense volcanic activity. This produces clusters in both time and space, reflecting conducive environments of high volcanic activity, crustal permeability, structural ore traps, and conditions favouring preservation. Observations of modern analogues suggest they form widely in areas of submarine volcanism (e.g., Hannington et al 2005).

Although VMS deposits started forming in the Archean and continue forming today, global occurrences peak in the Paleozoic and Mesozoic, coinciding with times of supercontinent breakup and dispersion. In British Columbia, deposits range from Cambrian to Cretaceous. Paleozoic deposits are the most abundant, but the two largest known deposits (Britannia and Windy Craggy) are Mesozoic (Massey, 1999). Mesozoic rocks host the most ore delineated to date and ore of the highest value, such as Eskay Creek (Jurassic), notable for its high precious metals tenor. The geographic distribution of VMS deposits spans much of the province west of Ancestral North America (Fig. 2). Modern sea floor deposits occur offshore, along the Juan de Fuca Ridge.

3.2. VMS classification

Early classification schemes (Table 1) relied heavily on metal associations and were named by type-region models: Kuroko (Zn-Pb-Cu); Besshi (Zn-Cu); and Cyprus (Cu ± Zn). Later schemes incorporated rock associations and tectonic settings. In the Piercey et al. (2015) scheme (Table 2) elements of Barrie and Harrington (1999), Franklin et al. (2005), Galley et al. (2007), and Piercey (2011) were combined. Herein we use terminology of the mineral deposit profiles developed by the British Columbia Geological Survey between 1995 and 2012, recently compiled and with some revisions by (Lefebure and Jones, 2022). Revisions to the marine volcanic association class ('G') include splitting what was previously designated as 'G06 Noranda/Kuroko type' into G06 Kuroko and G08 Noranda types (Lefebure and Jones, 2022). In some cases, individual deposits are hybrids and cannot be assigned a unique type. For example, deposit profile G07, 'hybrid volcanogenic massive sulphide Ag-Au (hybrid bimodal-felsic)' of Lefebure

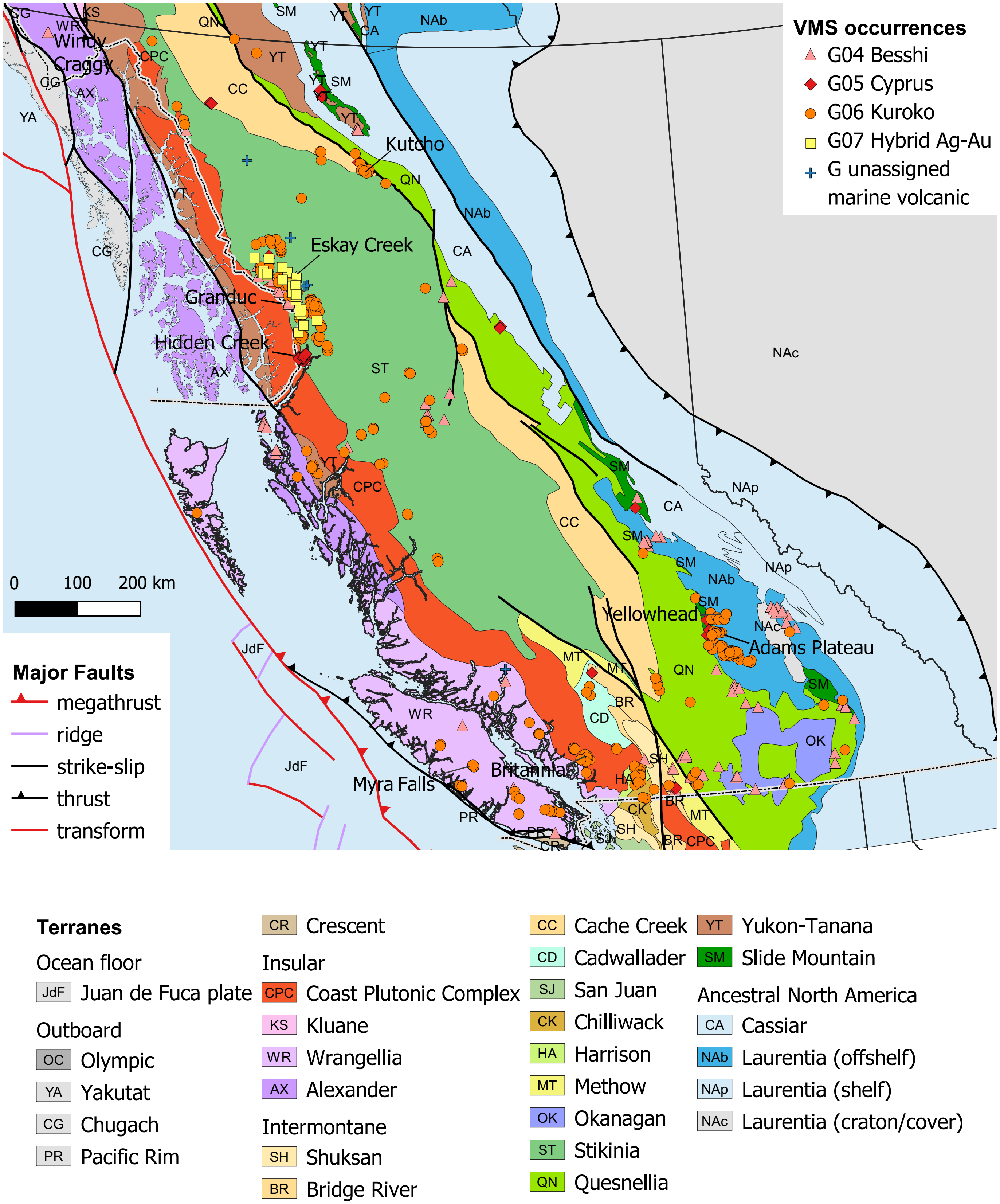

Fig. 2a. VMS occurrences by type with respect to terranes of the Canadian Cordillera. Terranes from Yukon Geological Survey (2020) and Colpron and Nelson (2021).

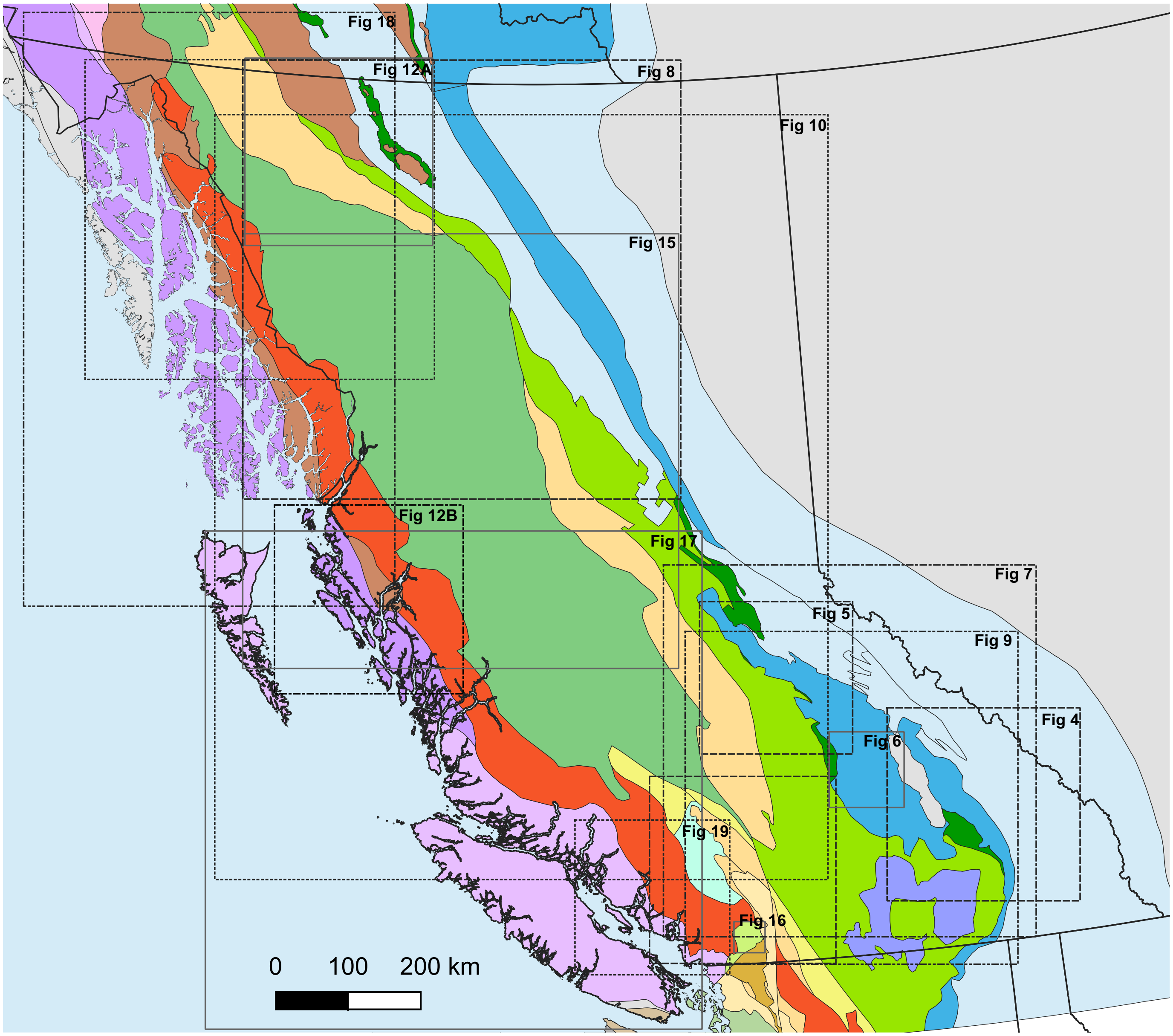

Fig. 2 b. Index to detailed maps presented in Figures 4 to 19.

and Jones (2022) overlaps with the Noranda and Kuroko types, as in the case of the Eskay Creek deposit. Or deposits of the Anyox camp bear similarities to both Cyprus type or Noranda type (Lefebure and Jones, 2022). Figure 3 shows relative base metal concentrations for British Columbia deposits for which resource estimates are published.

3.3. VMS deposit types in British Columbia

The treatment that follows accepts the VMS classification assigned to individual occurrences in the MINFILE database, while acknowledging that these assignments are subject to revision as occurrences are better understood and classification schemes evolve. Despite uncertainty in individual assignments, broad patterns emerge.

Approximately two thirds of the nearly 600 VMS MINFILE occurrences are assigned to the Kuroko (G06) and Noranda (G08) deposit types. Besshi style (G04) are next most abundant, followed by Cyprus type (G05) and subaqueous hot springs (G07). These occurrences generally cluster into areas based on stratigraphy and geographic location and based on mineral association and type (Fig. 3). Taking a terrane approach, ten areas that host deposits with more than 0.5 Mt production or resources are described below (Fig. 2).

4. VMS deposits in British Columbia by terrane

The Cordilleran orogen records a history of supercontinent rifting followed by collisions between the westward-driven North American continental plate and a series of island arc volcanosedimentary and intrusive assemblages that developed outboard of Ancestral North America and accreted to each

Table 1. VMS classification schemes. This paper uses terminology from the British Columbia Geological Survey mineral deposit profiles developed between 1995 and 2012. It includes a revision by Lefebure and Jones (2022) to the marine volcanic association class ('G') which splits G06 (Noranda-Kuroko) into G06 (Kuroko) and G08 (Noranda).

Sawkins 1976	**Solomon 1976**	**Franklin et al. 1981**	**Barrie and Hannington 1999**	**Franklin et al. 2005**	**Galley et al. 2007**	**Shanks and Koski 2012**	**Piercey 2011**	**Lefebure and Jones, 2022**
Kuroko	Zn-Pb-Cu	Zn-Pb-Cu	Bimodal-siliciclastic	Siliciclastic-felsic Mature epicontinental backarc Zn-Pb±Cu	Felsic-siliciclastic	Siliciclastic-felsic	Felsic-siliciclastic (Zn-Pb-Cu)	G07 Hybrid G06 Kuroko
			Bimodal-felsic	Bimodal-felsic Nascent or primitive epicontinental arc and related backarcs Zn-Pb-Cu	Bimodal-Felsic	Bimodal-felsic	Bimodal-felsic (Zn-Pb-Cu)	G06 Kuroko
			Bimodal-mafic	Bimodal-mafic Oceanic arc Cu-Zn	Bimodal-mafic	Bimodal-mafic	Bimodal-mafic (Zn-Cu)	G08 Noranda
Besshi	Zn-Cu	Cu-Zn	Mafic-siliciclastic	Pelitic-mafic Mature oceanic backarc Cu-Zn-Co	Pelitic-mafic	Siliciclastic-mafic	Mafic-siliciclastic (Cu-Zn-Co)	G04 Besshi
Cyprus	Cu	Cu-Zn	Mafic	Mafic Oceanic backarc Cu-Zn	Backarc mafic	Mafic-ultramafic	Mafic (Cu-Zn)	G05 Cyprus

Table 2. Classification of Piercey et al. (2015).

VMS sub-type	Rock types	Ore hosts	Metals	Tectonic setting	Alternative classification	Examples
Felsic siliciclastic	Bimodal sequences with felsic volcanic and volcanosedimentary rock > mafic rocks. Abundant graphitic sedimentary rocks and iron formation.	Felsic volcanic, volcaniclastic, and sedimentary rocks.	Zn-Pb-Cu-(AgAu)	Continental rifts, continental arc rifts, backarcs.	Bathurst-type. Iberian Pyrite Belt-type. Zn-Pb-Cu-type.	Bathurst district and Iberian pyrite belt.
Bimodal felsic	Bimodal sequences with felsic>mafic. rocks.	Felsic volcanic rocks.	Zn-Pb-Cu (Au-Ag)	Rifted continental arcs.	Kuroko-type Zn-Pb-Cu- type.	Kuroko district, Mount Read belt, Skellefte and Bergslagen districts.
Bimodal mafic	Bimodal sequences with mafic rocks>>felsic rocks.	Felsic volcanic rocks>>mafic rocks.	Cu-Zn-Pb-(Au- Ag)	Rifted primitive arcs ± backarc (MORB-rich) and forearc (boninite-rich).	Noranda-type. Cu-Zn-Pb.	Noranda and Flin Flon-Snow Lake districts; some deposits in middle and southern Urals.
Mafic siliciclastic	Mafic volcanic with mafic and ultramafic intrusive rocks and abundant siliciclastic rocks.	Mafic volcanic and/or mafic/ultramafic intrusive rocks.	Cu-(Co-Zn-Ni)	Backarc and forearc; ridges.	Besshi-type. Cu-(Co)-rich. Outokumpu-type. Pelitic mafic.	Besshi district, Japan, Windy Craggy, Outokumpu.
Mafic	Mafic volcanic and intrusive rocks, ± ultramafic rocks; commonly ophiolitic.	Mafic extrusive and intrusive rocks; rarely ultramafic rocks.	Cu-Zn	Backarc, forearc, and midocean ridge.	Cyprus-type. Cu-rich.	Cyprus, Oman, Appalachian ophiolites (e.g., Little Deer, Tilt Cove, Bay of Islands).

other and to the ancient continental margin (Fig. 2; Nelson et al., 2013a,b; Colpron and Nelson, 2021). The Cordillera continues to evolve with the Juan de Fuca plate sliding beneath Vancouver Island. In the eastern part of the orogen, autochthonous and parautochthonous basement of Ancestral North America is overlain by Proterozoic to Triassic cover rocks; farther west are mainly allochthonous terranes consisting of volcanosedimentary and allied plutonic rocks that represent magmatic arcs, accretionary complexes, and oceanic crust. These terranes are overlain by postaccretionary siliciclastic deposits and intruded by postaccretionary plutons (Nelson et al., 2013a,b; Colpron and Nelson, 2021).

4.1. Ancestral North America (shelf)

VMS deposits have not been confirmed in Ancestral North American (Laurentia) shelf strata. One possibility is the Wisconsin (082FSE036), a gold-silver prospect in the Horsethief Creek Group (Monk Formation, Neoproterozoic). At the Main zone of the prospect is a footwall of interbedded sedimentary and basaltic volcanic rocks and a hanging wall of quartzite and schist. With an historical inferred resource of 136,065 t 11.99 g/t Au and 171.4 g/t Ag, the zone also contains copper, lead, and zinc sulphides. Although MINFILE records the prospect as Besshi type, it could be a remobilized SEDEX, similar to J&L (see below; MINFILE 082M 003; Carpenter and Grant, 1985).

4.2. Ancestral North America (offshelf)

Parautochthonous subterranes (Kootenay and equivalent Barkerville) in the offshelf region of Ancestral North America (Fig. 2) host volcanogenic massive sulphide deposits concentrated in three broad spatial and temporal (early Cambrian to Early Mississippian) clusters. The Lardeau Group and Snowshoe Group host several Besshi occurrences,

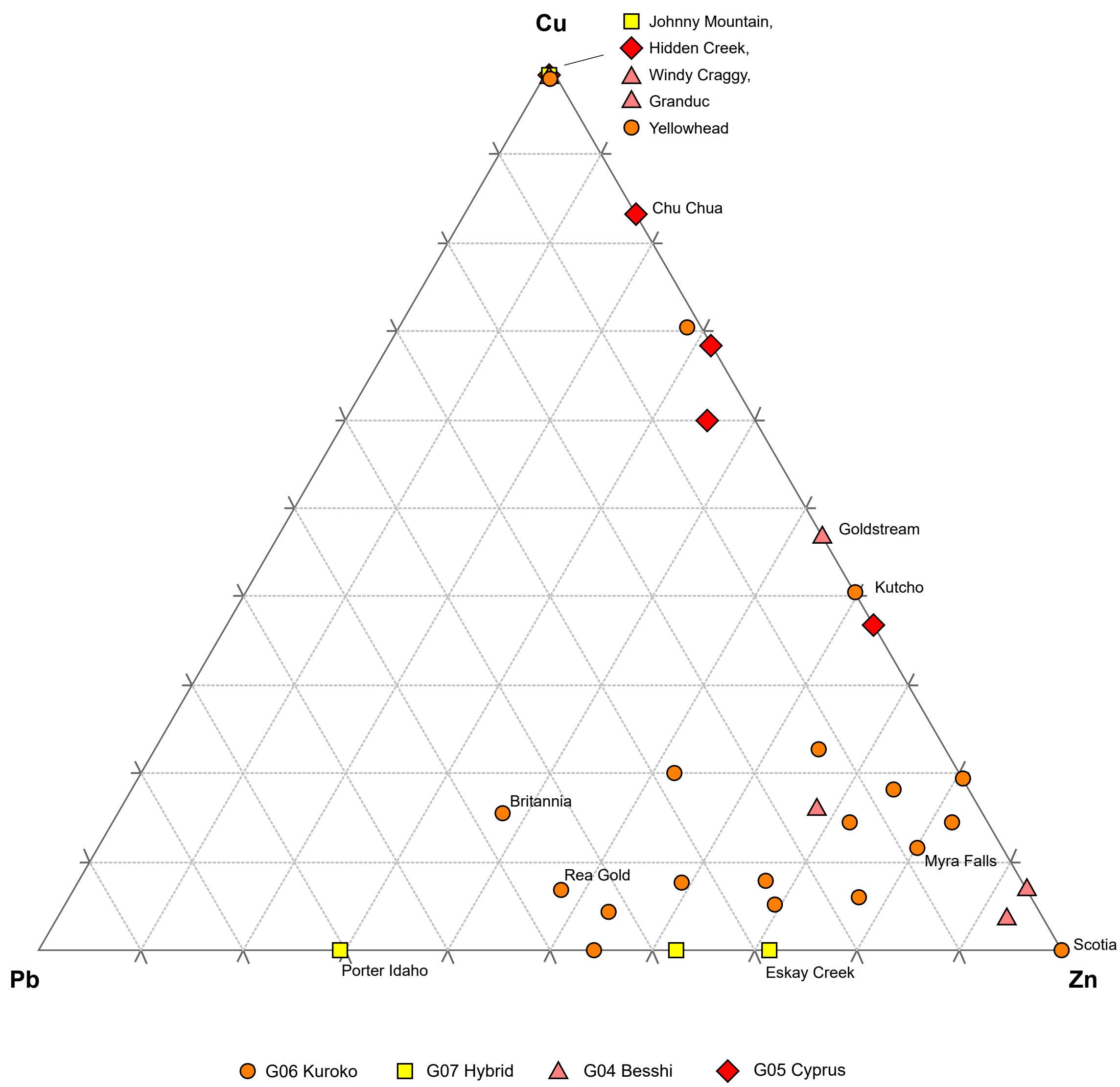

Fig. 3. Relative base metal concentrations in selected British Columbia VMS deposits.

including the past-producing **Goldstream** deposit. Eagle Bay assemblage rocks host Kuroko mineralization including the advanced **Yellowhead** project and past-producing **Samatosum** deposit.

4.2.1. Lardeau Group, Index Formation, lower-middle (?) Cambrian

Interlayered sedimentary and basaltic rocks of the Index Formation, formed on the rifted continental margin of Ancestral North America, have Besshi-type copper-zinc-silver mineralization (Logan and Colpron, 2006). The past-producing **Goldstream** deposit (Fig. 4) is the most developed of these, with 2.2 Mt mined between 1983 and 1996 recovering silver, gold, copper, zinc and minor cadmium and antimony. Remaining reserves are 22,000 t 3.5% Cu and 2.15% Zn. The deposit is in sericitic quartzite and calcareous chloritic phyllite in a metavolcanic-phyllite division (Höy, 1979, Logan and Colpron, 1995, Colpron et al. 1995). The horizon hosting the Goldstream deposit can be traced along several km in the Index Formation. Other probable Besshi type prospects in the Index Formation include **C-1**, hosted by rocks correlated with footwall rocks at Goldstream, **Spire**, about 7.5 km southwest of Goldstream, **Montgomery**, hosted by the same unit, and **Standard Basin**, about 30 km southeast of Goldstream (Fig. 4).

The **Ledgend** deposit (082KSE092) is a nickel-cobalt-copper bearing massive pyrrhotite showing approximately 200 km south-southeast of the Goldstream camp (Fig. 4), one of several targets apparently in the lower part of the Index Formation. These black phyllite-hosted occurrences with spatially associated altered ultramafic rocks, may be analogous to the Outokumpu and Talvivaara deposits in Finland and have been the subject of recent work (Drobe, 2018, Mihalynuk, 2019). Outokumpu itself has been compared to SEDEX and VMS

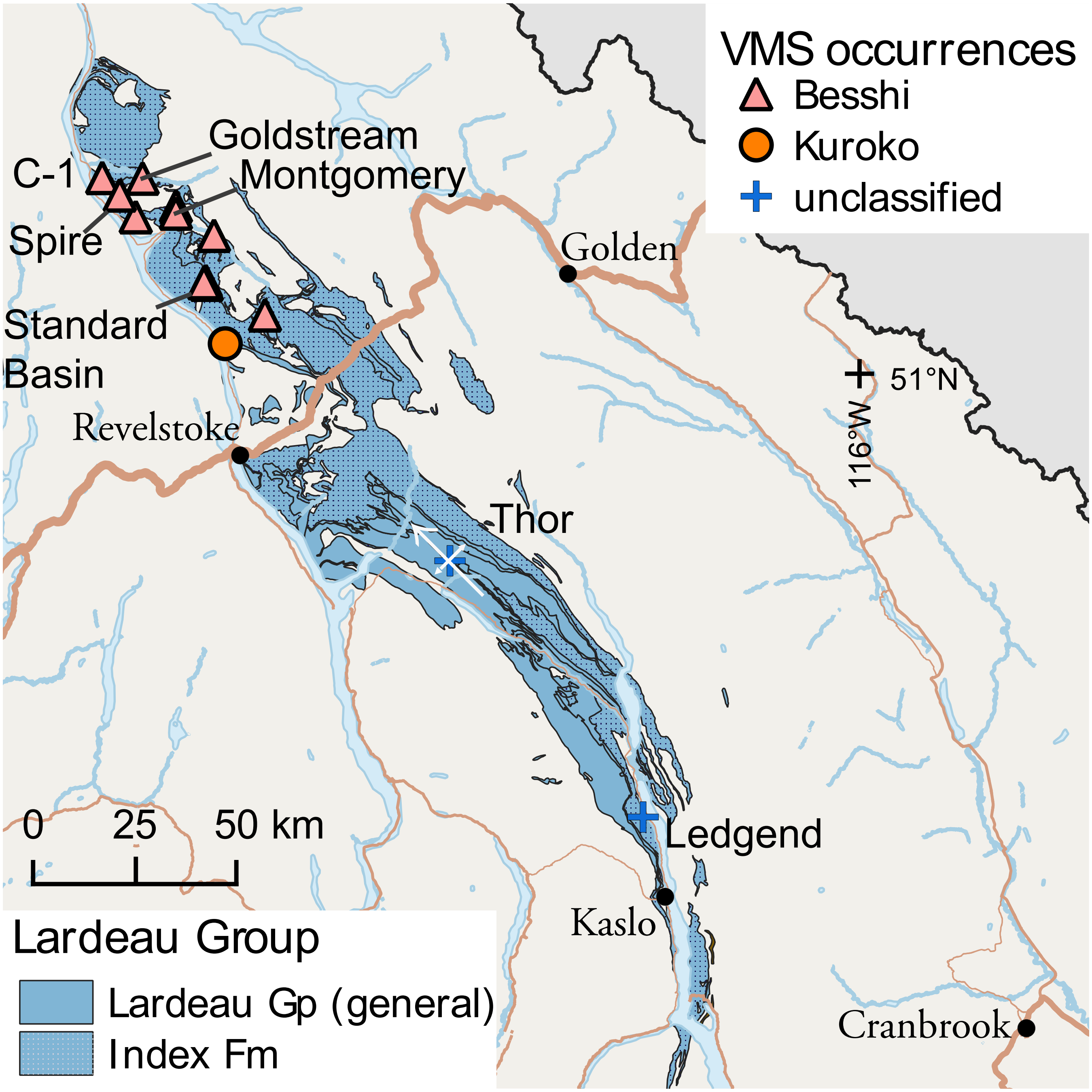

Fig. 4. Lardeau Group VMS deposits, offshelf region of Ancestral North America. See Figure 2b for location.

models and considered a deposit type of its own (Peltonen et al., 2007).

Occurrences on the eastern limb of the Thor antiform such as on Taranis Resources Inc.'s **Thor** project (Fig. 4) have been described as VMS-style silver-lead-zinc-gold-copper mineralization, possibly in the Jowett Formation of the Lardeau Group (McDonough, 2013; see also Blue Bell 082KNW060, Broadview 082KNW031, True Fissure 082KNW030, St Elmo 082KNW062, Great Northern 082KNW061).

4.2.2. Snowshoe Group, lower Paleozoic

In the offshelf region of Ancestral North America, the Barkerville subterrane is mainly underlain by the Snowshoe Group, a Proterozoic to Paleozoic package of predominantly siliciclastic rocks (Fig. 5; Ferri and Schiarizza, 2006). A cluster of Besshi and probable Besshi VMS occurrences in the Harveys Ridge succession (or its fine-grained equivalent Hardscrabble Mountain succession) in the Snowshoe Group northeast of Likely is hosted by lower Paleozoic metasedimentary siltstones,

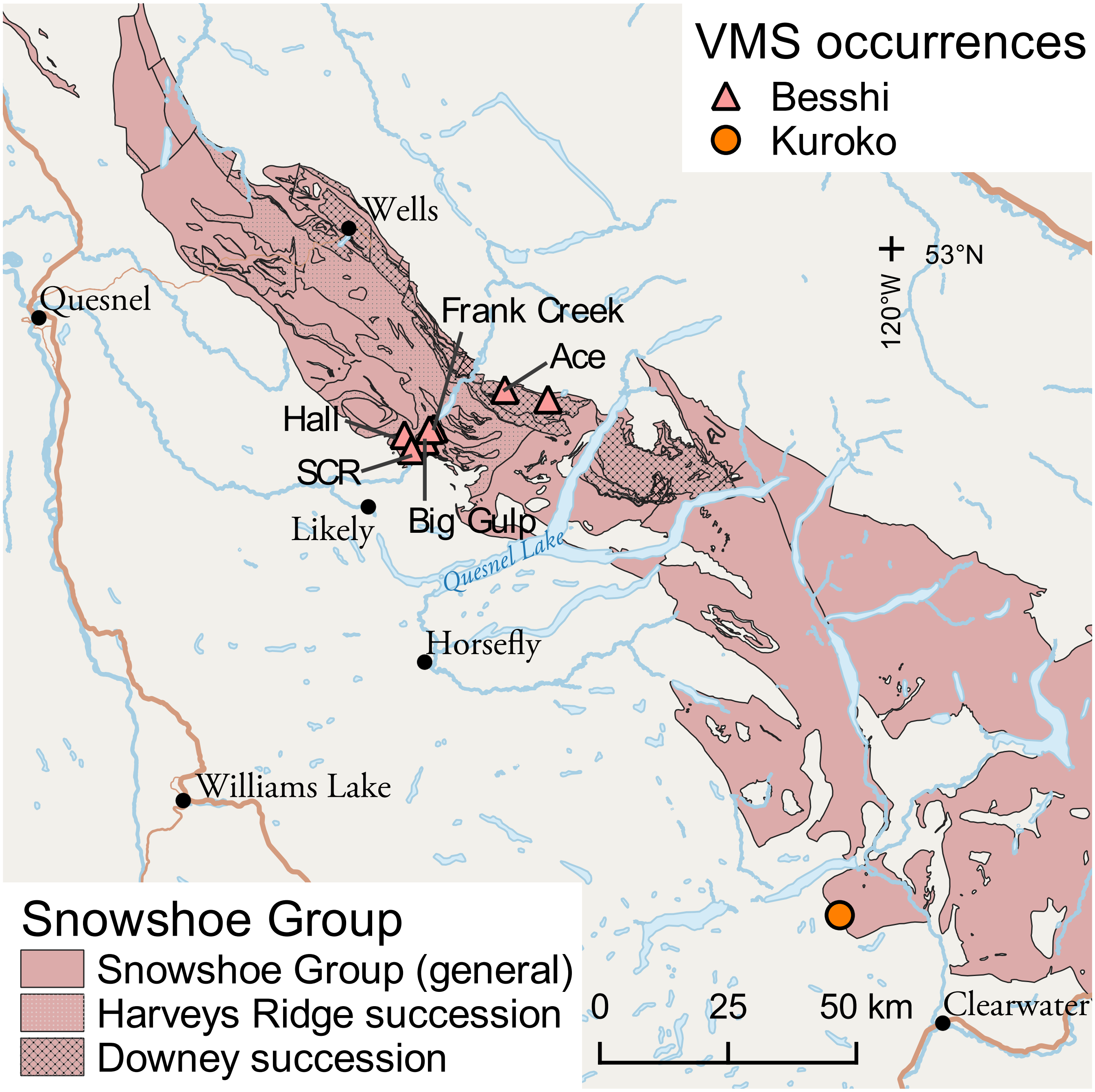

Fig. 5. Snowshoe Group VMS deposits, offshelf region of Ancestral North America (Barkerville subterrane). See Figure 2b for location.

phyllites, and metavolcanic rocks. These rocks are correlated with the lower part of the Index Formation, which hosts the Goldstream deposit (see above; Schiarizza and Ferri, 2003).

The Snowshoe Group occurrences are at grassroots and early exploration stages. The most-explored of these is the **Frank Creek** (MINFILE 093A 152, 093A 267) gold, copper, lead prospect. Others include **SCR** (093A 203), **Big Gulp** (093A 143), **Hall** (093A 337). **Ace** (093A 142) is mapped within the stratigraphically underlying Downey succession. Correlatives of the Devonian-Mississippian volcanic rocks that host Kuroko type deposits in the Eagle Bay assemblage to the south (Fig. 6 ; Ferri and Schiarizza, 2006; and see below) may be absent from the Snowshoe Group.

4.2.3. Eagle Bay assemblage and Fennell Formation, lower Cambrian-Mississippian

In the Adams Plateau area, the Eagle Bay assemblage (Lower Cambrian-Mississippian) of the Kootenay subterrane (the southern continuation of the Barkerville subterrane) and the Fennell Formation (Devonian-Permian) of the Slide Mountain terrane to the west (Fig. 6) host syngenetic sulphide deposits in multiple stratigraphic units. In contrast to the Lardeau and

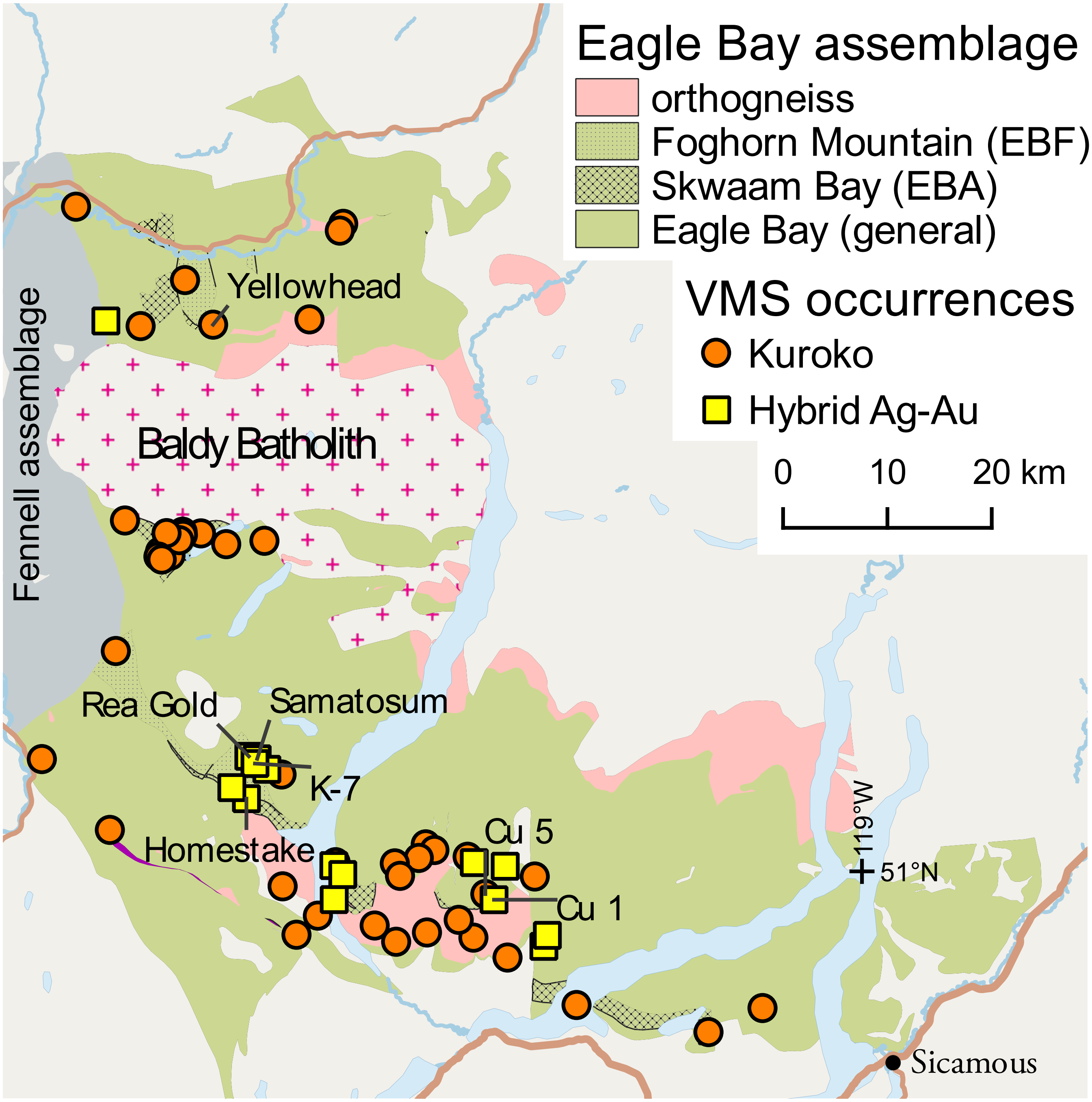

Fig. 6. Eagle Bay assemblage VMS deposits, offshelf region of Ancestral North America (Kootenay subterrane). See Figure 2b for location.

Snowshoe Groups, most of these deposits are considered Kuroko type. Many are highly silver enriched, possibly consistent with the hybrid Ag-Au (G07) model (Lefebure and Jones, 2022). Lower Cambrian alkalic ocean island basalt to subalkalic mid-ocean ridge basalts are consistent with a continental rift that never fully evolved into an oceanic basin (Paradis et al., 2006). Felsic volcanic rocks have not been recognized in the Cambrian succession, but Devonian-Mississippian strata include felsic and intermediate volcanic rocks and associated Kuroko-type (or hybrid) VMS deposits. These deposits occur with subalkalic mafic to felsic rocks interpreted to have formed in an extended continental arc with an associated back arc basin (Paradis et al., 2006).

Deposits assigned to a Kuroko type model are hosted mainly by unit EBA (Devonian) and overlying EBF (Devonian-Mississippian; Schiarizza and Preto, 1987; Höy, 1999). The deposits mostly cluster south of the Baldy batholith (Fig. 6), but they are also found to the north, such as **Yellowhead**, an advanced copper project. Many of the southern occurrences are silver-enriched (e.g., **Homestake**, **Samatosum**). Some probable mafic-type VMS showings are in unit EBG (Paradis et al, 2006).

Yellowhead (Formerly Harper Creek, 082M 009) is interpreted as a remobilized and attenuated polymetallic volcanogenic deposit (Collins et al., 2014) in metavolcanic and metasedimentary rocks of unit EBA. Original syngenetic mineralization may be consistent with a Kuroko style deposit. A 2020 feasibility update by Taseko Mines estimates Proven and Probable reserves of 817 Mt 0.28% Cu, 0.030 g/t Au, 1.3 g/t Ag (Taseko Mines Limited, 2020). Mineralization has a vertical zonation with an upper lead-zinc-silver-barite zone and a deeper copper-silver-gold zone (Clarke et al., 2021). South of the Baldy batholith, precious metals enriched VMS occurrences in unit EBA include **Homestake** (082M 025), and in unit EBF include **Samatosum** (082M 244), and **K-7** (082M 277). Unit EBG also hosts VMS including **Cu1** (082M 138) and **Cu5** (082M 139) which Paradis et al. (2006) considered as mafic volcanic associated and older than the more precious metals-enriched deposits.

4.3. Slide Mountain terrane

The Slide Mountain terrane is an oceanic assemblage containing interbedded mid-ocean ridge basalts and Mississippian chert and quartz clast-bearing sandstones and conglomerates. The terrane originated as a Late Devonian to Permian back-arc basin between the North American continental margin and Devonian-Permian arcs to the west and ultimately fully developed into an open ocean up to 3,000 km wide (Slide Mountain ocean, Nelson et al., 2013b). The Slide Mountain terrane contains several mafic volcanic-hosted occurrences. Most are classified in MINFILE as Cyprus type, but in the southeast (Fig. 7) two have Besshi type characteristics (**Mayflower**, **True Blue**), and at least one is considered Kuroko style (**Joseph** Ag-Pb-Zn occurrence). The most developed deposit is the **Chu Chua**, in the Fennell Formation. Several Cyprus-type occurrences are in northern British Columbia (Fig. 7).

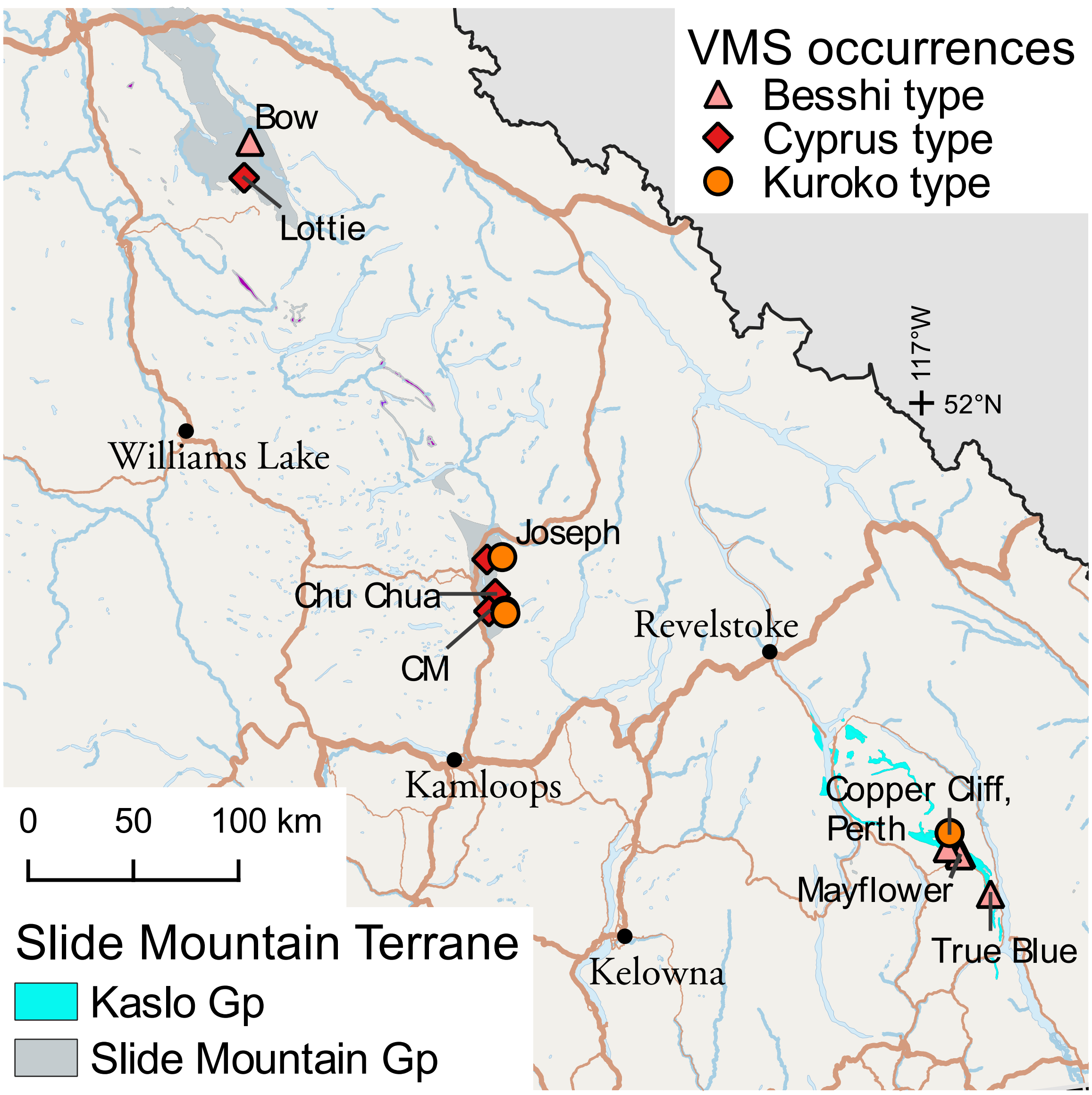

Fig. 7. Southern Slide Mountain terrane VMS deposits. See Figure 2b for location.

4.3.1. Slide Mountain Group (Fennell Formation) Devonian-Permian

Chu Chua (092P 140), hosted by massive and pillowed basalts of the Slide Mountain Group (Fig. 7; Fennell Formation; Upper Devonian-Middle Permian), is the most advanced of the Slide Mountain VMS with a 2021 pit-constrained resource estimate of 2.289 Mt 2.11% Cu, 0.30% Zn, 9.99 g/t Ag and 0.50 g/t Au in the inferred category at a 1.0% Cu cut off. Aggarwal (1982) noted cobalt in the ore zone at concentrations of 310-475 ppm. Chu Chua and the less-advanced **CM** occurrence (092P 101, Cu-Zn-Au-Ag) are consistent with the Cyprus model. **Joseph** (082M 194), in Permian rocks of the Fennel Formation has up to 3% Pb, as reported in drill reports, and is interpreted as Kuroko type (e.g., von Einsiedel, 2018).

4.3.2. Slide Mountain Group (Antler Formation), Mississippian

Bow (093H 033) is a copper-zinc showing in Mississippian volcanic rocks of the Slide Mountain Group (Antler Formation; Fig. 7). The showing consists of boulders of pyrite with up to 10% chalcopyrite and is referred to as a Cyprus deposit in MINFILE. **Lottie** (093H 156) is a copper +/- lead and zinc showing also in Antler Formation volcanic rocks. The showing consists of mineralized float (chalcopyrite, chalcocite, pyrite, minor bornite), the bedrock source of which has not been identified. Small pieces of float also contain galena, sphalerite, and native copper.

4.3.3. Kaslo Group, Permian

Mayflower (082KSW078) is a zinc-lead-silver possible Besshi showing in an area of Kaslo (Permian) and Slocan (Triassic) Group rocks (Fig. 7). Leontowicz (1974) described pods of sphalerite, galena, and tetrahedrite along a sheared contact between Slocan Group slate and Kaslo Group greenstone. **True Blue** (082FNE002) is a past producer of copper, silver, and gold along the contact between Kaslo Group volcanic rocks and Upper Mississippian-Permian sedimentary rocks of the Milford Group. Mineralization includes pyrite, pyrrhotite, chalcopyrite, minor galena, and sphalerite in a sericite schist and is considered Besshi-type. **Perth** (082KSW079) and **Copper Cliff** (082KSW111) are adjacent massive sulphide copper-zinc-lead-silver-gold occurrences described as bands and lenses of massive to semi-massive sulphides within Kaslo Group andesites or in intercalated sedimentary rocks. Sulphides consist of pyrrhotite, pyrite, sphalerite, and minor galena. The sulphide mineralogy and host lithology are consistent with a Kuroko model.

4.3.4. Nina Creek Group (Mount Howell Formation), Pennsylvanian-Permian, northern British Columbia

Nina (093N 011) is a gold-silver-copper-zinc prospect in the Nina Creek Group (Fig. 8), hosted mainly by shears in gabbros of the Mount Howell Formation. Massive pyrite with variable chalcopyrite and minor sphalerite are considered as sheared Cyprus mineralization (see Ferri et al., 1994).

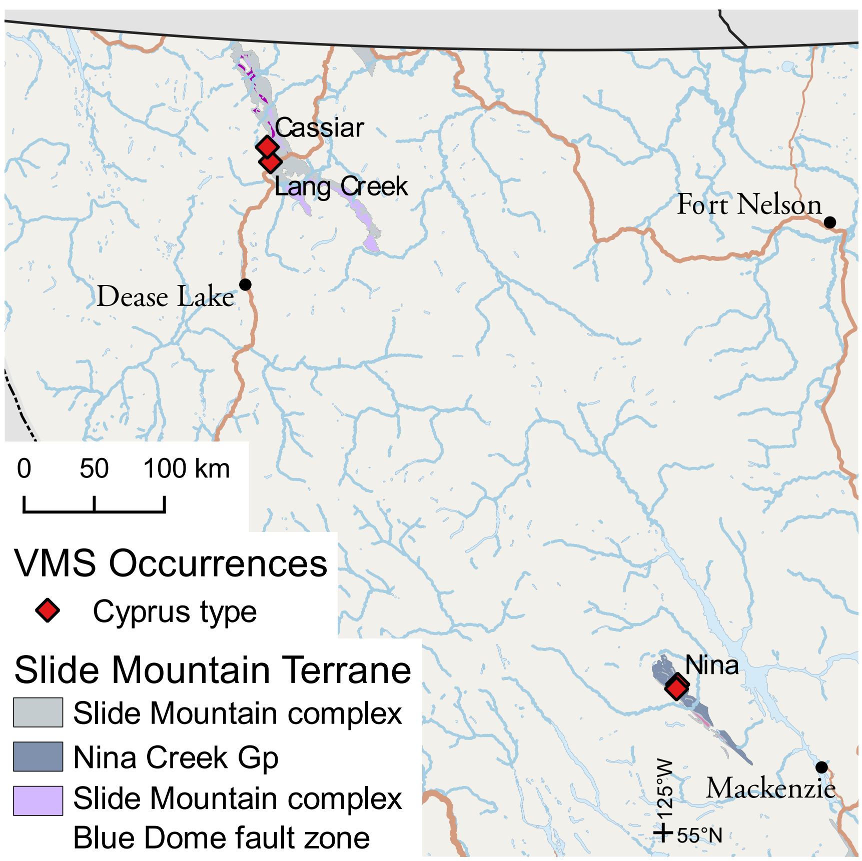

Fig. 8. Northern Slide Mountain terrane VMS deposits. See Figure 2b for location.

4.3.5. Slide Mountain complex, northern British Columbia

Lang Creek (104P 008) is a copper-zinc prospect (Fig. 8) that has seen little exploration since 1980. In addition, a small massive sulphide showing was exposed in the pit wall of the **Cassiar** asbestos mine (104P 114, 104P 005)

4.4. Quesnel terrane

Although numerous (Fig. 9), none of the VMS occurrences in Quesnel terrane (or Quesnellia) have been developed to the extent of a significant resource or large-scale production.

4.4.1. Quesnel basement, Carboniferous-Permian

VMS occurrences in Quesnel terrane basement are in rocks of the Anarchist Group, Knob Hill Group, and Kobau metamorphic complex (Fig. 9). **Libra** (082ESW075), probably the most advanced, is a Besshi prospect in andesites of the Old Tom Formation, which is lithologically similar to the Knob Hill complex (Massey and Dostal, 2013). Based on a single drill hole, **Boot** (082ESW100) is reported as a copper-silver-nickel Besshi showing in the Old Tom Formation (cf. Ledgend, in Lardeau Group, above). **Lexicon** (082ESE124) is a Besshi

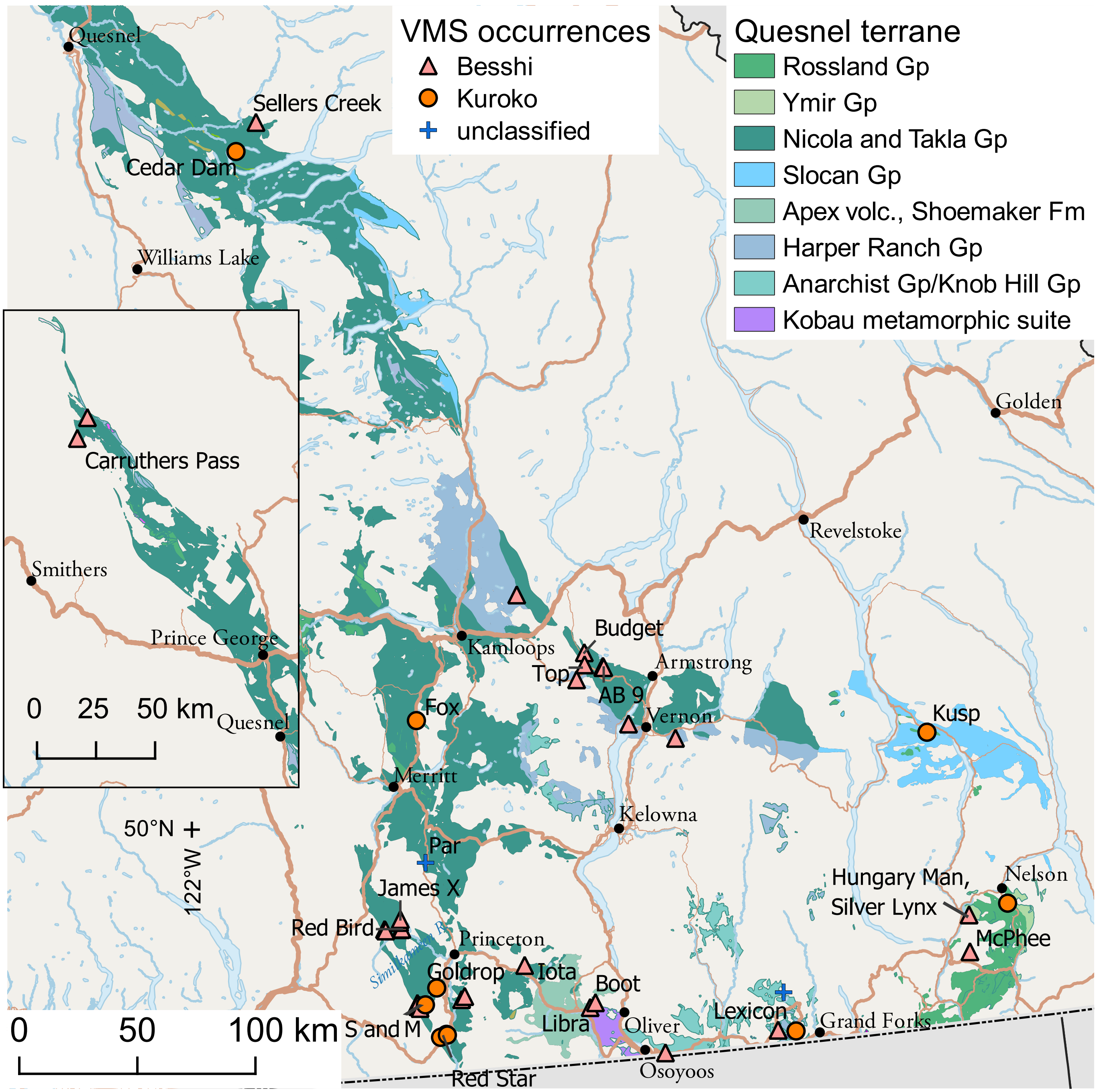

Fig. 9. Southern Quesnel terrane VMS deposits. See Figure 2b for location.

copper showing in the Knob Hill complex.

4.4.2. Nicola Group, Takla Group (Upper Triassic)

Although not traditionally considered prospective for VMS, the Nicola Group hosts clusters of occurrences. A cluster of Besshi occurrences (**St. George** 092HNE064, **Red Bird** 092HNE020, **James X** 092HNE016) is northwest of Princeton (Fig. 9). Also, in the Similkameen River area, southwest of Princeton is a cluster of Kuroko-style occurrences. Although neither **Red Star** (092HSE067) nor **S and M** (092HSE073) have been significantly developed, the two produced a few tonnes of polymetallic ore in the 1960s. **Goldrop** (092HSE124) produced 345 t of gold-silver-copper-lead-zinc ore in the 1970s. A cluster of Besshi-style occurrences west of Vernon, including **Top** (082LNW085), **AB 9** (082LSW067) and **Budget** (082LNW035) appear to be in the Nicola Group, but this remains uncertain. Occurrences are also mapped in the Harper Ranch Group. The **Falkland** (082LNW001) anhydrite/gypsum deposit may be volcanogenic, as inferred for ore bodies at Britannia (Butrenchuk, 1991).

Documented VMS occurrences are otherwise scattered in Nicola and Takla rocks. **Iota** (092HSE119) shipped 68 tonnes of ore in 1950 and 1951, yielding gold, silver, lead, and zinc. **Fox** (092ISE191) is a Kuroko-style prospect northeast of Merritt. **Carruthers Pass** (094D 172) is a Besshi style copper-zinc silver prospect in Takla Group sedimentary rocks approximately 200 km north of Smithers.

Atypical VMS deposits could be previously unrecognized targets in the Nicola Group (Galley et al 2007). For example, Mihalynuk et al. (2014) suggested the possibility of VMS mineralization in bimodal submarine volcanic rocks. **Par** (092HNE169) has characteristics of both VMS and high sulphidation epithermal mineralization (Mihalynuk et al., 2014), raising the possibility of atypical (shallow marine), precious metals-enriched synvolcanic mineralization in the Nicola Group.

4.4.3. Rossland Group, Elise Formation, Lower Jurassic

In southeastern Quesnellia, the Rossland Group is a Lower Jurassic arc assemblage with VMS mineralization in the Elise Formation, a sequence of volcanic and epiclastic rocks (Fig. 9). Volcanism began in the late Sinemurian with submarine shoshonitic flows in eastern exposures (Höy and Dunne, 2001). Eastern subaqueous volcanosedimentary successions host at least one occurrence identified as VMS, **McPhee** (082FSW375), a polymetallic (gold-silver-copper-zinc-lead-nickel-cobalt-tungsten-molybbdenum) showing in a roof pendant of the Bonnington pluton (Middle Jurassic). The MINFILE classification is Besshi type, although other deposits in the area (BW, Maud S, Free Gold) are in veins and interpreted to be related to Bonnington magmatism or Eocene structures (Caron, 2010). The **Kusp** (082KSW161) is a Kuroko type lead, zinc, silver prospect. Showings in the Ymir Group (Lower Jurassic) have a possible marine volcanic association (**Hungary Man** 082FSW235, **Silver Lynx** 082FSW378).

4.5. Cache Creek terrane and Kutcho assemblage

Cache Creek oceanic units host several Cyprus and a few Besshi type occurrences (Fig. 10), but the most advanced deposit is in the Kutcho island arc assemblage, which hosts Kuroko type occurrences, notably the **Kutcho Creek** deposit, a feasibility stage proposed mine. Correlative rocks may also be prospective for VMS (Schiarizza, 2013).

4.5.1. Kutcho, Sitlika, and Wineglass assemblages and Venables Valley assemblage (Permo-Triassic)

In northern British Columbia, the Cache Creek accretionary complex hosts a few mafic-hosted Mississippian-Permian VMS occurrences (Fig. 10). In the south, are Permian-Jurassic mafic-hosted and mafic-sediment hosted occurrences. The most advanced VMS prospect, the **Kutcho** copper-zinc-lead-silver-gold deposit, is hosted by a primitive Permo-Triassic oceanic arc traditionally included in the Cache Creek terrane, but considered distinct from it (Mihalynuk et al., 2017).

The Kutcho assemblage is a Late Permian-Early Triassic package of felsic and mafic metavolcanic rocks (schists) in the King Salmon allochthon, which separates exposures of the Cache Creek terrane to the north and Stikine terrane to the south. Schiarizza (2013) correlated the Kutcho assemblage with the Sitlika volcanic unit and Wineglass assemblages to the south and possibly felsic volcanic and intrusive rocks of the Venables Valley belt, previously assigned to Nicola Group. The Sitlika assemblage and Venables Valley rocks also host Kuroko-type occurrences, though none has been developed. **Kutcho** (104I 060) is a Kuroko type zinc-copper-lead-silver-gold deposit in the Kutcho assemblage (Lower Triassic to uppermost Permian; Childe and Thompson, 1997; Schiarizza, 2012). It has a 2011 (re-stated 2017) reserve estimate of 10.4 Mt 2.01% Cu, 3.19% Zn, 0.37 g/t Au, and 34.6 g/t Ag. Kuroko-type showings in Kutcho assemblage rocks to the northwest include **Castle** (104I 077) and **Groovin** (104I 138).

The Sitlika and Wineglass assemblages in central and southern British Columbia, have been correlated with the Kutcho assemblage based on lithologic similarity, ages, stratigraphic setting, and relationship with structurally overlying Cache Creek complex rocks (Schiarizza, 2013). The Sitlika assemblage contains a number of likely volcanogenic showings (e.g., **Bodwar North** (093N 251), **Eureka** (093N 179), **Bodwar South** (093N 250). The **LLL** (092O 068) showing consists of pyrite, pyrrhotite, and minor disseminated chalcopyrite. Diamond drill sludge returned silver values. The **Red Hill** (092INW042), **Silica** (092INW057) and **Spatsum** (092INW054) prospects (Fig. 10) are in rocks tentatively correlated with the Kutcho assemblage. A U-Pb zircon age and tholeiitic lithogeochemistry support the correlation (Childe et al., 1997), but the structural position at the eastern margin of the Cache Creek terrane remains problematic (Schiarrizza, 2013). The lithology (felsic volcanic) and ore mineralogy (copper-zinc-lead) are consistent with Kuroko-style models.

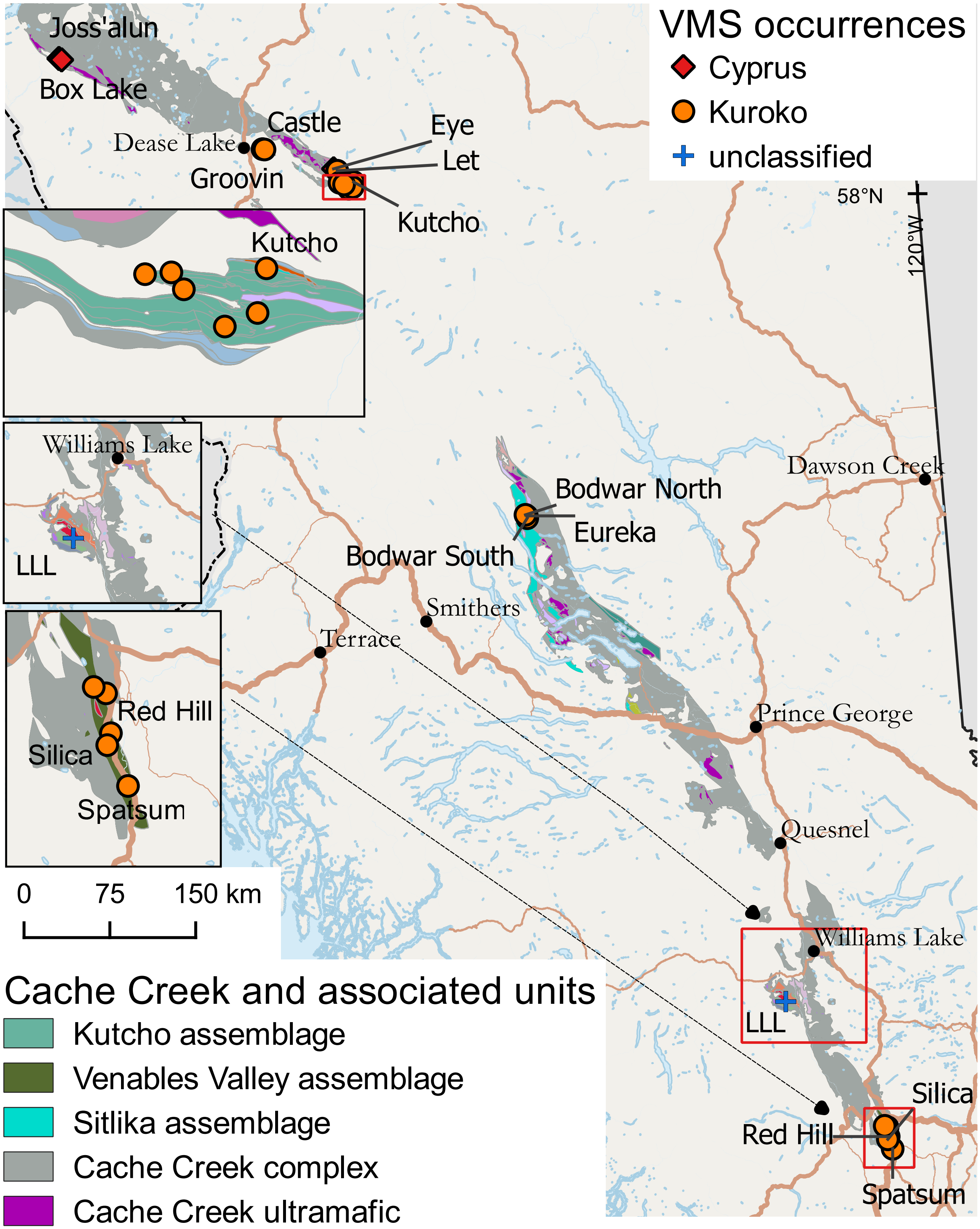

Fig. 10. Cache Creek terrane and Kutcho assemblage and equivalents VMS deposits. See Figure 2b for location.

4.5.2. Cache Creek complex

Northwest of Dease Lake (Fig. 10), the Cache Creek complex hosts **Joss'alun** (104N 136) a Cyprus-style occurrence consisting of semi-massive chalcopyrite and pyrite in predominantly mafic volcaniclastic rocks of the Nakina Formation (upper Mississippian to Permian), **Box Lake** (104N 139) a similar showing, and **Eye** (104I 076) a pyrite, pyrrhotite, chalcopyrite showing. The **Let** (104I 074) is a chalcopyrite showing about 250 km southeast in a sericite schist/metarhyolite unit of the Cache Creek complex.

4.6. Bridge River terrane

The Bridge River oceanic terrane in southern British Columbia (Figs. 2, 11) is close in age to the Cache Creek terrane (Mississippian to Middle Jurassic). It hosts Besshi and Cyprus deposits such as **Wayside** (092JNE121), a pyrite-predominant massive sulphide occurrence in greenstones with an historical (1985) resource of 150,000 t 1.76% Cu, 3.03% Zn. **Krof** (092HNW070) is a copper-zinc-silver-gold prospect in rocks of the Cogburn schist, which are probably equivalent to the Bridge River complex. Sulphides consist of pyrite, chalcopyrite, and lesser sphalerite in mixed metasedimentary and metavolcanic rocks. The possibly correlative Hozameen complex also hosts some VMS mineralization, such as **North Star** (092HSW076), now within Skagit Valley Park.

4.7. Yukon-Tanana and correlative terranes

In the Yukon-Tanana terrane (Fig. 2) south of Prince Rupert is the 80 km-long Ecstall greenstone belt (Fig. 12a). The belt represents a mid-Devonian volcanic arc overlain by a package of metasedimentary rocks. These rocks are in turn overlain by mafic gneiss, interpreted as having a late Devonian volcanic protolith. Alldrick and Jackaman (2002) noted 40 sulphide showings along the belt, with many clustered near the central **Ecstall** deposit (Fig. 12a), which was first reported in 1890. Three Kuroko deposits have historical resource estimates.

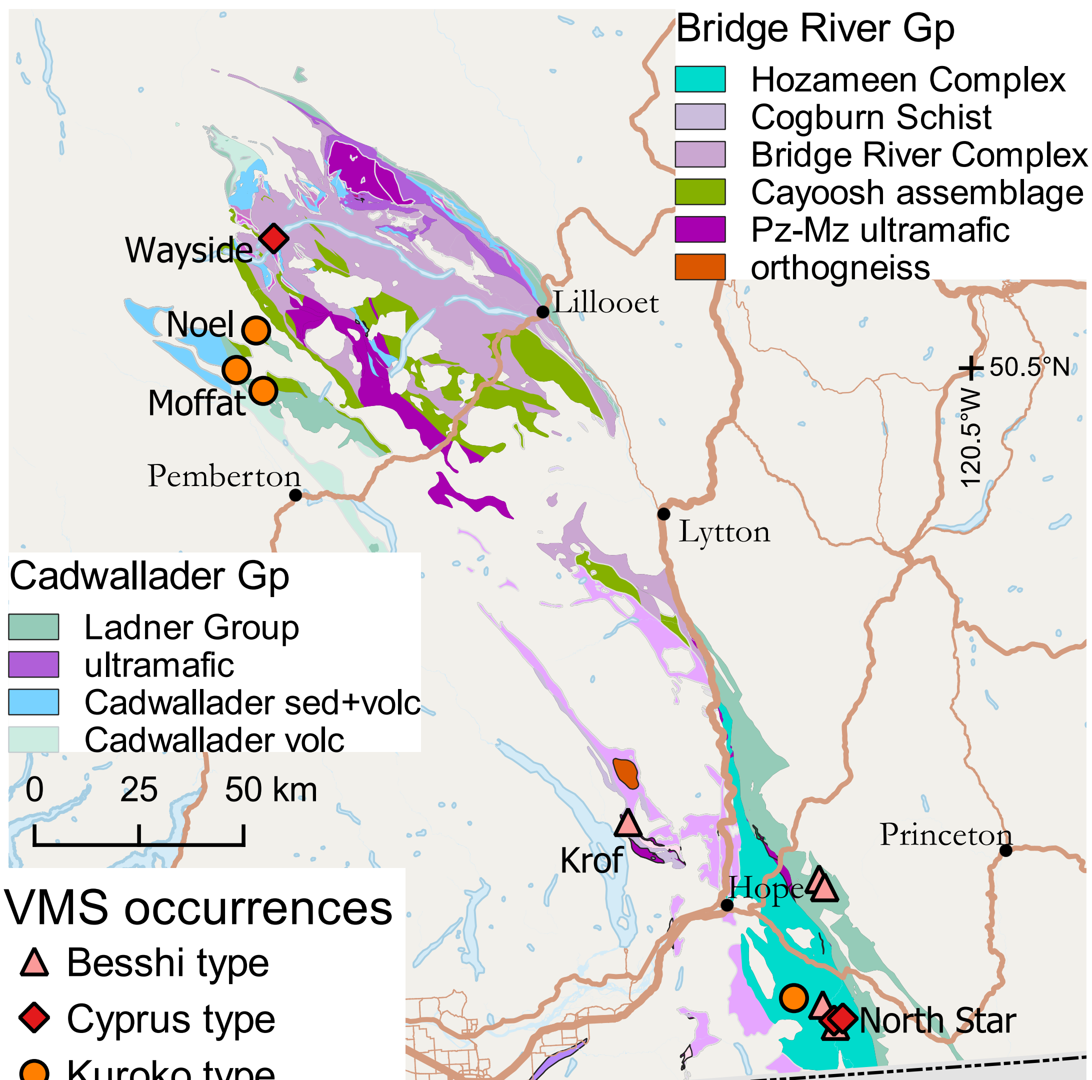

Fig. 11. Bridge River terrane and Cadwallader terrane VMS deposits. See Figure 2b for location.

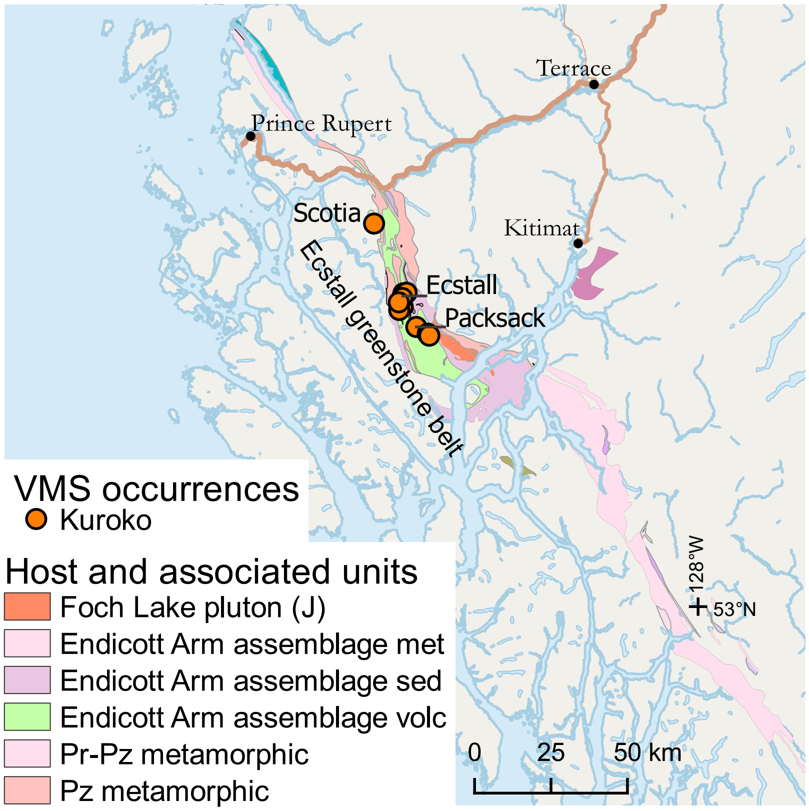

Fig. 12a. Southern Yukon-Tanana terrane VMS deposits. See Figure 2b for location.

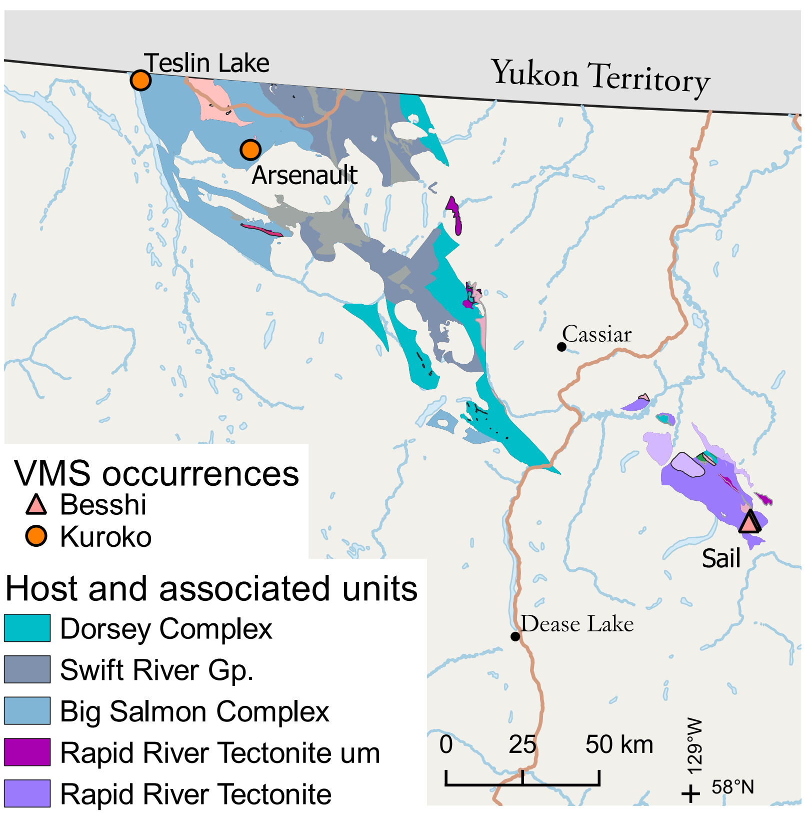

Fig. 12 b. Northern Yukon-Tanana terrane VMS deposits. See Figure 2b for location.

Despite the apparent potential and exploration dating back to the 19th century, recent exploration has been limited, focussing mainly on the northernmost prospect (**Scotia**). To the north in Yukon, the Yukon-Tanana terrane hosts the Early Mississippian Kudz Ze Kayah and Wolverine deposits.

4.7.1. Ecstall greenstone belt (Middle Devonian)

Scotia (103I 007) is a zinc-lead-silver-copper-gold deposit of probable Paleozoic age in a north-northwest trending belt of metamorphosed volcanic and sedimentary rocks stretching from Hawkesbury Island to the mouth of the Skeena River (Fig. 12a). Mineralization at the Albere zone consists of massive to semi-massive sphalerite with lesser pyrite, galena, pyrrhotite, magnetite, and chalcopyrite. Harrington and Giroux (2017) reclassified an existing estimate as a compliant Inferred resource of 632,000 t 7.60% Zn, 19.75 g/t Ag, 0.11% Cu, 0.28 g/t Au, and 0.74% Pb using a $75/t net smelter return cut off. Mineralization is described as Kuroko style, and hosts are metamorphosed mafic and felsic volcanic rocks.

Ecstall (103H 011) is an iron-sulphur (pyrite)-copper-zinc-silver-gold-lead deposit. Mineralization is predominantly pyrite with minor chalcopyrite and sphalerite and lesser pyrrhotite, marcasite, and galena. A 1993 estimate by Atna Resources Ltd. had 6,349,700 t 20.0 g/t Ag, 0.5 g/t Au, 0.5% Cu, and 2.5% Zn. This estimate may have been based on 1950s era work; a 1957 estimate by Texas Gulf was 8 million tons with no grade stated. **Packsack** (103H 013) is copper-zinc-silver-gold-lead-iron deposit with similar Kuroko mineralization consisting of massive pyrite with minor chalcopyrite, chalcocite, and sphalerite. A 1987 Falconbridge report described Packsack as having a 'reserve' of approximately 2.7 Mt of 0.5% Cu, 0.2% Zn, 0.01% Pb, 34 g/t Ag, and 0.3 g/t Au.

4.7.2. Rapid River tectonite

Interpreted as Yukon-Tanana basement (Ryan et al., 2015) the Rapid River tectonite hosts a cluster of Besshi copper-zinc-gold silver occurrences called the **Sail** showings (Fig. 12b).

4.7.3. Big Salmon complex

The Big Salmon complex (Fig. 12b) is thought to be partly equivalent to Yukon-Tanana terrane rocks in the Finlayson Lake area, Yukon (Mihalynuk et al., 1998) that host several VMS deposits (Yukon MINFILE occurrences): Fyre Lake (105G 034); Kudz Ze Kayah (105G 117); Wolverine (105G 072); and Ice (105G 118). The oldest rocks in the Big Salmon complex are cut by Middle Mississippian dioritic intrusive rocks (Mihalynuk et al., 2006). The **Arsenault** (104O 011) is hosted by metasedimentary and metavolcanic rocks of the Big Salmon complex. Arsenault is a stratabound copper-silver-gold prospect explored sporadically since 1967. **Teslin Lake** (104N 135) is another possible VMS showing, with pyrite+chalcopyrite mineralization in a 20 m-thick horizon of felsic metatuff underlain and overlain by mafic metatuff beds (Mihalynuk et al.,1998).

4.8. Stikine terrane

The Stikine terrane (or Stikinia; Fig. 2) is extraordinarily productive, with significant VMS mineralization in the basement Stikine assemblage and in overlying Stuhini and Hazelton groups. The Hazelton Group between the past-producing Eskay Creek mine and the Anyox camp is particularly prospective, including for the gold and silver-rich hybrid type, both within and outside the Eskay rift (Hunter et al., 2022).

4.8.1. Stikine assemblage, Devonian-Mississippian

The Stikine assemblage is a Paleozoic arc and sedimentary succession at the base of Stikinia. The most advanced VMS prospects, **Tulsequah Chief** and **Big Bull**, lie in a Devonian-Permian island arc sequence. To the southeast is a cluster of less-developed Kuroko deposits (Fig. 13).

Tulsequah Chief is (104K 002) is a Kuroko type zinc-copper-lead-silver-gold deposit in Lower Mississippian strata. It has a 2012 Indicated resource of 6.8 Mt 5.89% Zn, 1.19% Cu, 1.1% Pb, 2.4 g/t Au, and 86 g/t Ag. Cominco mined Tulsequah Chief and **Big Bull** between 1951 and 1957. Redfern Resources Ltd. reported a positive feasibility study in 1995, but the project never resumed production. The **Big Bull** (104K 008) Kuroko copper-zinc-lead-silver-gold deposit has an estimate (2010) of 231,000t 3.22% Zn, 1.2% Pb, 0.38% Cu, 152 g/t Ag, and 2.9 g/t Au in the Indicated category and 728,000 t 5.61% Zn, 2.42% Pb, 0.34% Cu, 185 g/t Ag, and 3.9 g/t Au in the Inferred category. **Foremore** (104G 148) is a silver-gold-zinc-lead prospect for which the geological setting, surface showings and drill intersections are consistent with Kuroko mineralization. **Maple Leaf** (104K 117) is a Zn-Pb-Cu-Ag-Au showing in rocks of the Boundary Ranges metamorphic suite equivalent (Currie and Parrish, 1997). **Big Thing** (104M 071) is another Zn-Pb-Cu-Ag-Au showing in either Boundary Ranges suite rocks or the Stuhini Group.

4.8.2. Stikine terrane, Stuhini Group (Late Triassic)

Mihalynuk (1999) interpreted the Stuhini Group as recording two major arc-building episodes. The resulting sedimentary and volcanic rocks host VMS style mineralization distinct in age from the Paleozoic Stikine assemblage syngenetic mineralization described above and the Late Triassic-Jurassic Hazelton Group described below. The **Granduc** past-producing mine (Fig. 14) appears to be hosted by the Stuhini Group (Childe 1997, Mihalynuk et al., 2019), although it occurs at the margin of what became the Eskay rift (Jurassic, Hazelton Group). The less-developed and possibly Besshi massive sulphide **Rock and Roll** is also likely Triassic. Occurrences with Kuroko or Besshi characteristics of probable Triassic age are also recorded north of Granduc (Fig. 14; e.g., **SMC, Inel**).

Granduc (104B 021) is a Besshi type (Höy, 1995a) copper-silver-gold deposit hosted in sheared rocks at a fault contact between the Stuhini and Hazelton groups. U-Pb dating by Mihalynuk et al., (2019) of upper mine series breccia is consistent with a younger age limit to mineralization of

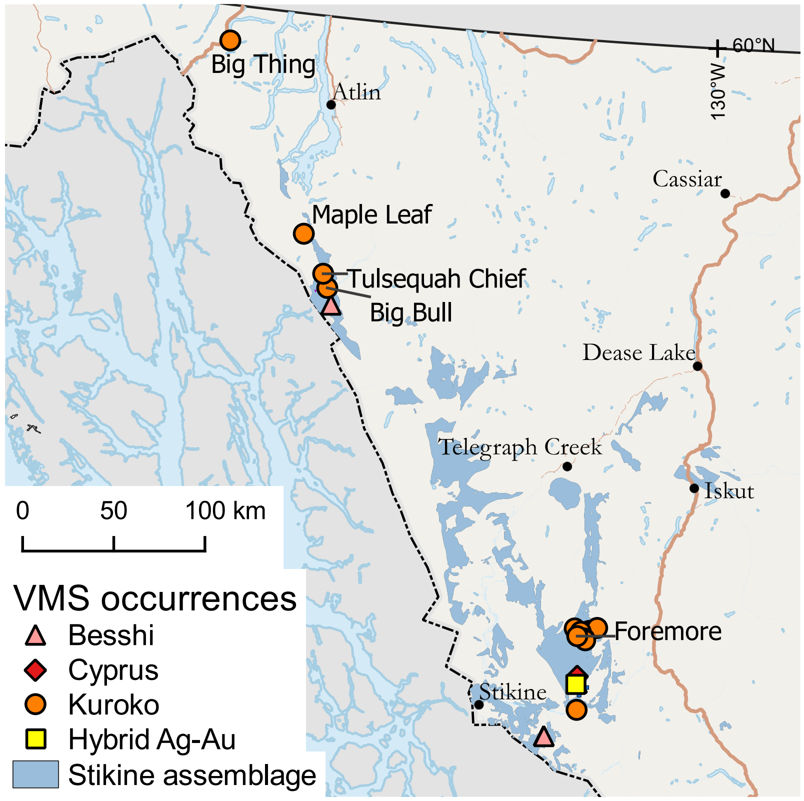

Fig. 13. Stikine assemblage VMS deposits. See Figure 2b for location.

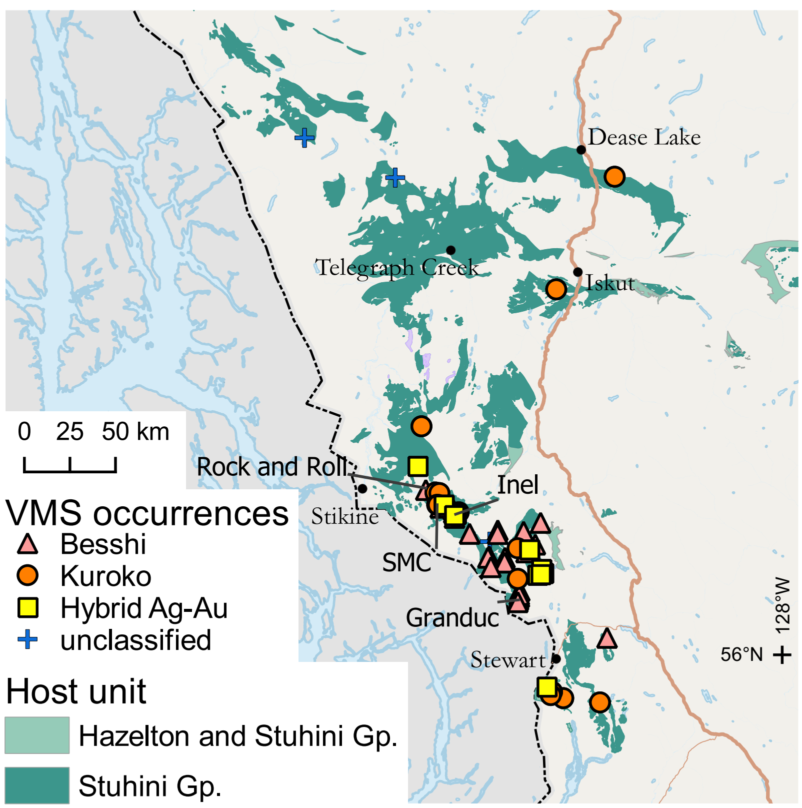

Fig. 14. Stuhini Group VMS deposits. See Figure 2b for location.

approximately 208 Ma. Prior to production in 1971, Granduc had reserves of 39.3 Mt at 1.73% Cu. It ultimately produced 190,143.7 t Cu, 64,303 oz Au, and nearly 4 million oz Ag from 15.6 Mt of ore by 1984. Castle Resources Inc. now holds the property and has a 2013 Main Zone resource of: 1) 5.16 Mt Measured at 1.58% Cu, 0.17 g/t Au, and 13.7 g/t Ag; 2) 6.16 Mt Indicated at 1.39% Cu, 0.17 g/t Au, and 11.4 g/t Ag; and 3) 30.52 Mt Inferred at 1.4% Cu, 0.17 g/t Au, and 13.3 g/t Ag. The North Zone has 14.11 Mt with 1.49% Cu, 0.21 g/t Au, and 5.2 g/t Ag in the Inferred category (Morrison et al. 2013). **Rock and Roll** (104B 377) is a zinc-lead-copper-gold-silver deposit with a 2011 indicated resource of 2,155,679 Mt 0.68 g/t Au, 82.7 g/t Ag, 0.22% Cu, 0.22% Pb, and 0.94% Zn (Jones et al., 2011). The deposit is largely hosted by graphitic argillite in contact with diorite (Jones et al., 2011) and is likely a Besshi deposit. Mihalynuk et al. (2019) bracketed the age between 210 and 292 Ma., broadly consistent with Granduc. **Inel** (104B 113) is a gold-silver-zinc-lead-copper prospect in marine sedimentary and volcanic rocks and appears to be both of intrusion-related vein and Besshi type. In the Discovery zone, bedding parallel pyrite-chalcopyrite-sphalerite-galena occurs in a sequence of thinly bedded sedimentary and volcanic rocks. Mineralization also occurs in veins and breccia dikes. A preliminary historic (non-compliant) resource of 317,485 t 0.1% Cu, 0.1% Pb, 2.6% Zn, 12.2 g/t Ag, and 3.3 g/t Au for Lens No. 1 in the Discovery zone was reported by Jaramillo and Gifford (1991). **SMC** (104B 567) is a gold-silver-lead-zinc-copper prospect in Stuhini Group (?) volcanic rocks. Significant results include a 2005 1m chip sample yielding 14.7 g/t Au, 16.4 g/t Ag and 1% Pb+Zn. Mineralization has characteristics of both Kuroko type and shear-hosted veins (Richards, 2008). The Cliff anomaly (104B 569) and other showings have possible Kuroko characteristics (e.g., Tillerman 104B 568, Ray 104B 076, Ray No. 2 104B 088).

4.8.3. Stikine terrane, Hazelton Group, Eskay rift (Late Triassic, Early-Middle Jurassic)

The Eskay rift is a 250 km long, north-south oriented discontinuous belt traceable from the Iskut area southward to Anyox (Fig. 15). It is interpreted as an Early-Middle Jurassic fault-bounded basin hosting thick accumulations of bimodal volcanic rock and intercalated sedimentary rocks of the Hazelton Group. Within these rocks are a number of significant gold and silver-rich VMS occurrences at different stratigraphic horizons. To date, the Eskay Creek mine has been by far the most productive of these northern, gold-enriched VMS deposits.

Eskay Creek (104B 008) is a subaqueous hot spring-Kuroko type precious metals-enriched massive sulfide deposit underlain by Lower-Middle Jurassic rocks in the upper part of the Hazelton Group. The Eskay Rhyolite member, immediate footwall of the deposit, was dated at 175+/-2 Ma (Childe, 1996). Between 1995 and 2007 Eskay Creek produced 3.2 million ounces of gold and nearly 159 million ounces of silver from just over 2 Mt of ore in several mineralized zones. North of Eskay Creek, occurrences along a 10-15 km north-south trend have some characteristics of VMS type mineralization, including the **RDN** prospect (104G 144), a gold-silver zinc-copper-lead polymetallic prospect near the top of the Hazelton Group. Polymetallic veins have been the target of exploration, but alteration at the Wedge zone is interpreted as representing the footwall of a shallow marine VMS (Awmack, 1999; Jones, 2005, 2006). Mortensen et al. (2005) dated felsic volcanic rocks in the lower part of the stratigraphic sequence at approximately 193 Ma, older than Eskay Creek.

To the south, rocks in the lower part of the Hazelton Group host several more gold-rich possible VMS and hybrid occurrences (Fig. 15). Interpretations vary. **Big Missouri** (104B 046) is a polymetallic vein deposit with disseminated, semi-massive and massive sulfide mineralization within the Stewart complex deformed volcanic, sedimentary, and metamorphic rocks in the lower part of the Hazelton Group. **Dago** (104B 045), is a silver-gold (lead-copper) deposit also in the lower part of the Hazelton Group. These have been interpreted in the past as forming is a subaqueous environment, although the more recent interpretation of mineralization in the Premier camp is intermediate sulphidation epithermal (Bird et al., 2020). **Porter-Idaho** (103P 089), also in lower Hazelton rocks, has massive galena, sphalerite, pyrite, tetrahedrite zones possibly consistent with an Eskay type hybrid VMS model.

4.8.4. Stikine terrane, Hazelton Group, upper Kitsault River, Upper Triassic, Early-Middle Jurassic

A cluster of silver-enriched VMS and possible VMS-epithermal hybrid occurrences is in Hazelton Group rocks near the headwaters of the Kitsault River (Fig. 15) including three past producers (**Torbrit, Dolly Varden, North Star**). Deposits have been variously described as exhalative stratiform, replacement, epithermal, and stockwork. This has led to an interpretation of shallow-marine to subaerial depositional environments, possibly analogous to Eskay Creek (Turner and Nicholls, 2019) though they may have slightly older maximum ages (ca. 188 Ma vs. Eskay Creek at 174 Ma) and are not confined to the main Eskay rift corridor (Hunter et al. 2022).

Torbrit (103P 191) is a probable hybrid type silver-enriched silver-lead-zinc-gold deposit in greenschist facies Hazelton Group pyroclastic rocks. Mining in 1928-29 and 1949-1959 produced 1.25 Mt of ore that yielded 18.6 million ounces of silver, 111 ounces of gold, 10.7 million pounds of lead, and 0.6 million pounds of zinc. A 2019 resource estimate has an Indicated resource of 2.623 Mt 296.8 g/t Ag and an Inferred resource of 1.185 Mt 278 g/t Ag (150 g/t cut off). **Dolly Varden** (103P 188) is a hybrid-type silver enriched silver-lead-zinc-copper deposit underlain by andesitic crystal vitric tuff and overlain by andesitic ash tuff. It was mined between 1919-21 and 1935-40 to produce 1.36 million ounces of silver, 2048 pounds of lead, and 421 pounds copper. A 2019 estimate has an Indicated resource of 156,000 t 414.2 g/t Ag, and an Inferred resource of 86,000 t 271.5 g/t Ag (both at a 150 g/t cut off). Mined in 1918 and 1921 to produce 2,838 ounces of

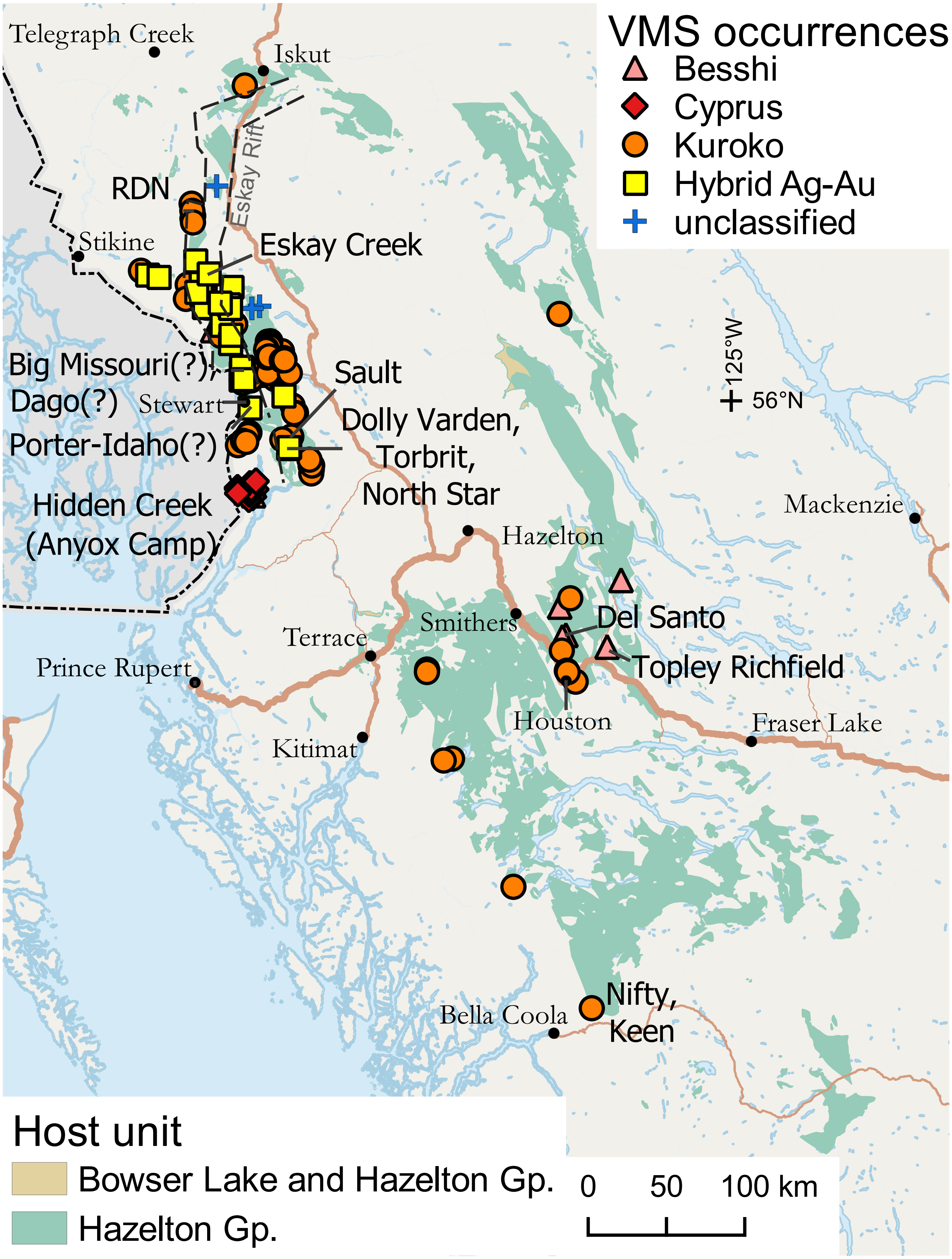

Fig. 15. Hazelton Group VMS deposits. Approximate location of Eskay Rift after Gagnon et al. (2012). See Figure 2b for location.

silver, **North Star** (103P 189) is a hybrid type silver-enriched deposit in exhalative rocks which, underlain by an andesitic crystal vitric tuff and overlain by andesitic ash tuff, are likely equivalent to the horizon hosting the Dolly Varden deposit. North of Dolly Varden are zinc showings, such as Sault (103P 233), with Kuroko VMS characteristics.

4.8.5. Stikine terrane, Hazelton Group, Anyox pendant (southern Eskay Rift), Early-Middle Jurassic

Interpreted as the southern extent of the Eskay Rift (Evenchick and McNichol, 2002; Alldrick, 2000, 2003, 2006), the Anyox mining camp includes several past producers, notably the **Hidden Creek** mine (Fig. 15), which produced more than 21 Mt of ore. A 1992 report for Taiga Consultants Ltd. cited a 24 Mt historical resource estimate. The Hidden Creek and a cluster of surrounding copper deposits are considered Cyprus, Besshi or Noranda VMS (Lefebure and Jones, 2022, cf. northern Eskay rift). Polymetallic veins were also bulk sampled or mined. These are in a roof pendant in the Coast Plutonic Complex of Lower to Middle Jurassic metasedimentary and metavolcanic rocks correlated with Hazelton Group rocks.

The **Hidden Creek** (103P 021) Cyprus-type copper-gold-silver-cobalt-zinc deposit is in a pendant of Hazelton Group basalts that are overlain by Bowser Lake Group rocks (Middle-Upper Jurassic; Evenchick and McNicoll, 2002) at the eastern margin of the Coast Plutonic Complex. Between 1914 and 1937, the deposit produced 21,725,534 t of ore at 1.4% Cu, 0.17 g/t Au, and 9.5 g/t Ag. A 1992 (historical) open-pit resource has 24,221,840 t 1.08% Cu, 0.17 g/t Au, and 10.3 g/t Ag. Many other past producers and prospects are in the Anyox camp (Fig. 15). Bonanza (103P 023) is a Cyprus-type copper-silver-gold deposit mined between 1928 and 1934. It has a 1993 estimate (historical) of 10,620 t 13.71 g/t Ag, 0.16 g/t Au, and 1.76% Cu. Redwing (103P 024) is a Cyprus type copper-silver-zinc-gold deposit with a 1966 estimate of 181,440 t 85.71 g/t Ag, 1.2 g/t Au, 2.0% Cu, and 2.7% Zn. Double Ed (103P 025) is a Cyprus type copper-zinc deposit with a 1960 (historical) estimate of nearly 2 Mt 1.3% Cu, 0.6% Zn. Eden (103P 026) is a polymetallic vein Cyprus type copper-zinc deposit with 1954 (historical) estimates of 122,470 t 1.3% Cu, and 1.3% Zn in a lower zone and 36,287 t 1.9% Cu, and 2.9% Zn in an upper zone. May (103P 027), Goldkeish (103P 045), Goldleaf (103P 028) are polymetallic veins mined or bulk sampled historically. Rambler (103P 226), Larcom Island (103P 227), Granby Point (103P 022), and Reserve Quartz (103P 252) were mined for quartz flux when the Anyox smelter was in operation.

4.8.6 Southern Hazelton Group

Other areas underlain by the Hazelton Group are also prospective for VMS, such as the Topley area north of Houston (Fig. 15). Besshi MINFILE occurrences include **Topley Richfield**, (093L 018) in the Saddle Hill Formation (Lower-Middle Jurassic) and **Del Santo,** 093L 025 in the Telkwa Formation (Lower Jurassic). The Telkwa Formation may also host Kuroko type occurrences. **Nifty** 093D 006 and **Keen** (093D 007) are possible Jurassic Kuroko type occurrences. Host rocks appear correlative with Hazelton Group at its southern extent. They are near a fault contact with the northern extent of the Gambier Group.

4.9. Harrison terrane, Harrison Formation (Early-Middle Jurassic)

The Harrison terrane (Middle Triassic-Early Cretaceous) is an inboard member of the Insular belt incorporating Early to Middle Jurassic arc sequences (Fig. 2; Dorsey, 2018). Intermediate to felsic volcanic rocks of the Harrison Formation (Weaver Lake member; Lower to Middle Jurassic) host a cluster of Kuroko sulphide occurrences (Fig. 16; McKinley, 2006). The **Seneca, Vent**, and **Fleetwood** are the most advanced.

Seneca (092HSW013) is a Kuroko or subaqueous hot spring zinc-copper-lead-silver-gold deposit. It has a 1983 (historical) resource estimate of 1.5 Mt 41.13 g/t Ag, 0.82 g/t Au, 0.63% Cu, 0.15% Pb, and 3.57% Zn. The last recorded drilling was in 2006. **Vent** (092HSW139) is a Kuroko prospect consisting of dacite-hosted stockwork veins with zinc, copper, lead, silver, and gold mineralization. **Fleetwood** (092HSW165) is a Kuroko zinc-copper-lead-gold prospect consisting of a massive sulphide layer (up to 1.35 m intersection) underlain by a stockwork zone hosted by felsic volcanic rocks. Less-developed **Bigfoot** (092HSW094), **Keiko** (092HSW140), **Kuro** (092HSW150), **SKU** (092HSW086), **LD** (092HSW070) and others are polymetallic vein and Kuroko type showings in the central part of the Harrison Lake Formation. LD has seen recent exploration drilling targeting gold and silver-bearing quartz-carbonate veins. **Scout Adit** (092HSW176), **Scout** (092HSW177), **Ascot** (092HSW072), **Fairplay** (092HSW031), and **Valley View** (092HSW015) represent a cluster of Kuroko type occurrences in the southern part of the Harrison Formation, historically explored for silver, gold, lead, zinc, and copper.

4.10. Wrangel terrane, Sicker Group (Late Devonian)

The Sicker Group, a Paleozoic (Devonian-Carboniferous) oceanic magmatic arc, forms the basement of Wrangell terrane (or Wrangellia). It hosts past zinc-copper-lead-silver-gold producers and prospects in the Mount Sicker area, a current producer (**Myra Falls**) in the Buttle Lake area, and additional zinc-lead-copper silver-gold occurrences in the Port Alberni, Tofino and Gold River areas (Fig. 17). Equivalent rocks on Moresby Island host a zinc-lead-gold-silver-copper-barite occurrence (**Cimadoro**103F 052). VMS occurrences are mostly bimodal-felsic, Kuroko type interpreted to have formed in an intra-arc rift (Juras, 1987).

Myra Falls (092F 071, 72, 73, 330) is a Kuroko (Höy, 1995b) zinc-copper-lead-silver-gold camp (multiple lenses) in Sicker Group rocks. The Myra Formation (Upper Devonian) hosts all deposits. More than 30 Mt of ore have been mined and milled at Myra Falls since 1966. Proven and Probable Reserves as of the end of 2014 were 5.87 Mt 5.92% Zn, 0.61% Pb, 0.85% Cu, 61.5 g/t Ag, 1.54 g/t Au. **Lara** (092B 129) is a Kuroko (Höy, 1995)

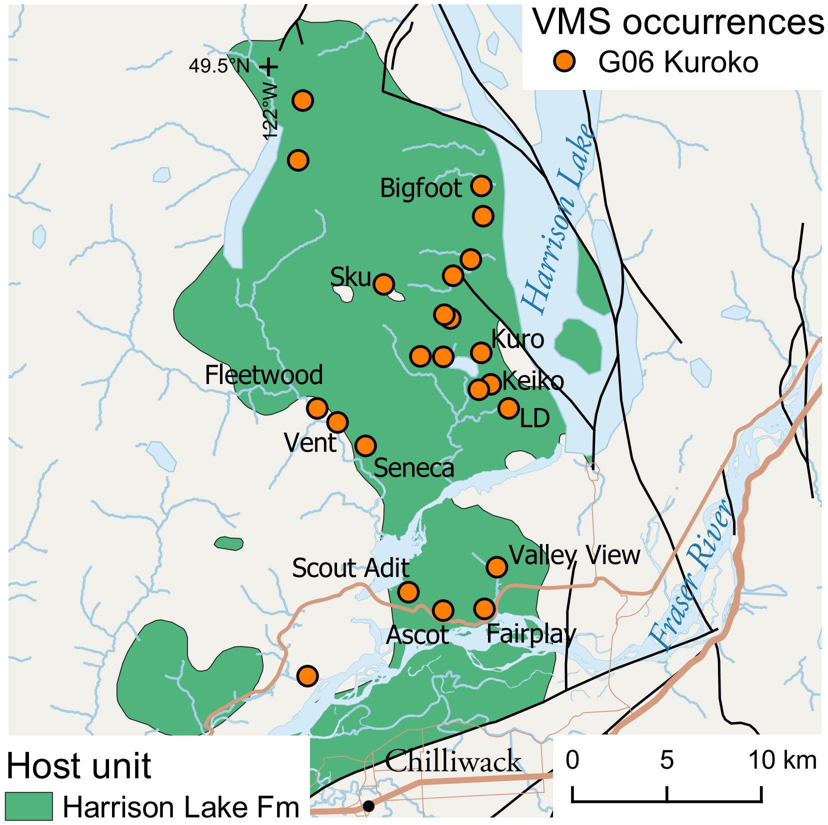

Fig. 16. Harrison Lake Formation VMS deposits. See Figure 2b for location.

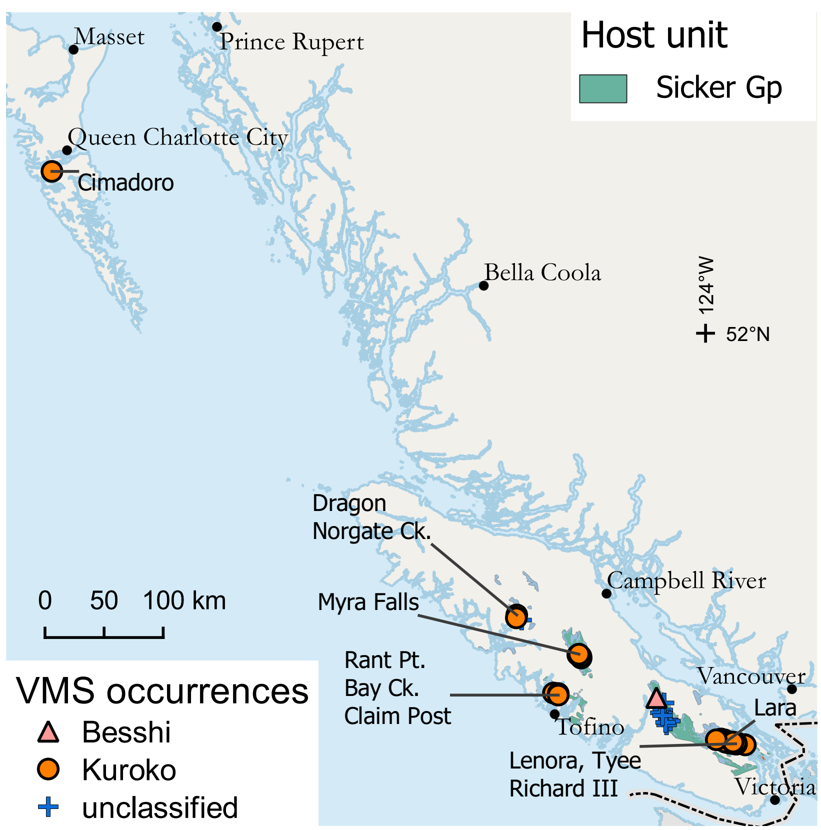

Fig. 17. Sicker Group VMS deposits. See Figure 2b for location.

zinc-lead-copper-silver-gold polymetallic prospect in Sicker Group rocks of the McLaughlin Ridge Formation. A package of quartz crystal, quartz-feldspar crystal, and fine tuffs host massive sulphides. A 2007 estimate has an Indicated resource of 1.1467 Mt 3.01% Zn, 1.05% Cu, 0.58% Pb, 32.97 g/t Ag, 1.97 g/t Au, and an Inferred resource and 669,600 t 2.26% Zn, 0.09% Cu, 0.44% Pb, 32.99 g/t Ag, 1.9 g/t Au. **Lenora, Tyee,** and **Richard III** (092B 001, 002, 003) are zinc-copper-lead-silver-gold past producers. Massive sulphides are hosted by the McLaughlin Ridge Formation felsic tuffs and sedimentary rocks. Setting and mineralization are consistent with a Kuroko deposit model. **Dragon** (092E 072) and **Northgate Creek Zone** (092E 083) are Zn-Pb-Cu-Au-Ag prospects in Sicker Group rocks exposed northeast of Nootka Sound. **Rant Point** (092F 494), **Bay Creek** (092F 343), **Claim Post** (092F 290) represent a small cluster of Zn-Cu-Pb-Ag-Au showings in the Bedwell Sound area. At **Cimadoro** (103F 052), lenses of massive to semi-massive Zn-Pb-Cu-Au-Ag-barite mineralization occur at a fault contact between possible Sicker Group and Buttle Lake equivalent rocks and Vancouver Group basalts (Karmutsen Formation).

4.11. Alexander terrane

VMS mineralization in the Alexander terrane falls into two broad groups, Mesozoic in the north and likely Paleozoic in the south. The Tats Group (Triassic) hosts **Windy Craggy** (Fig. 18), the largest known VMS in British Columbia; the equivalent Hyd Group in Alaska hosts the Greens Creek mine, a major producer of silver.

4.11.1. Ordovician

Pit (103H 066) is a copper-lead-zinc-silver-gold prospect

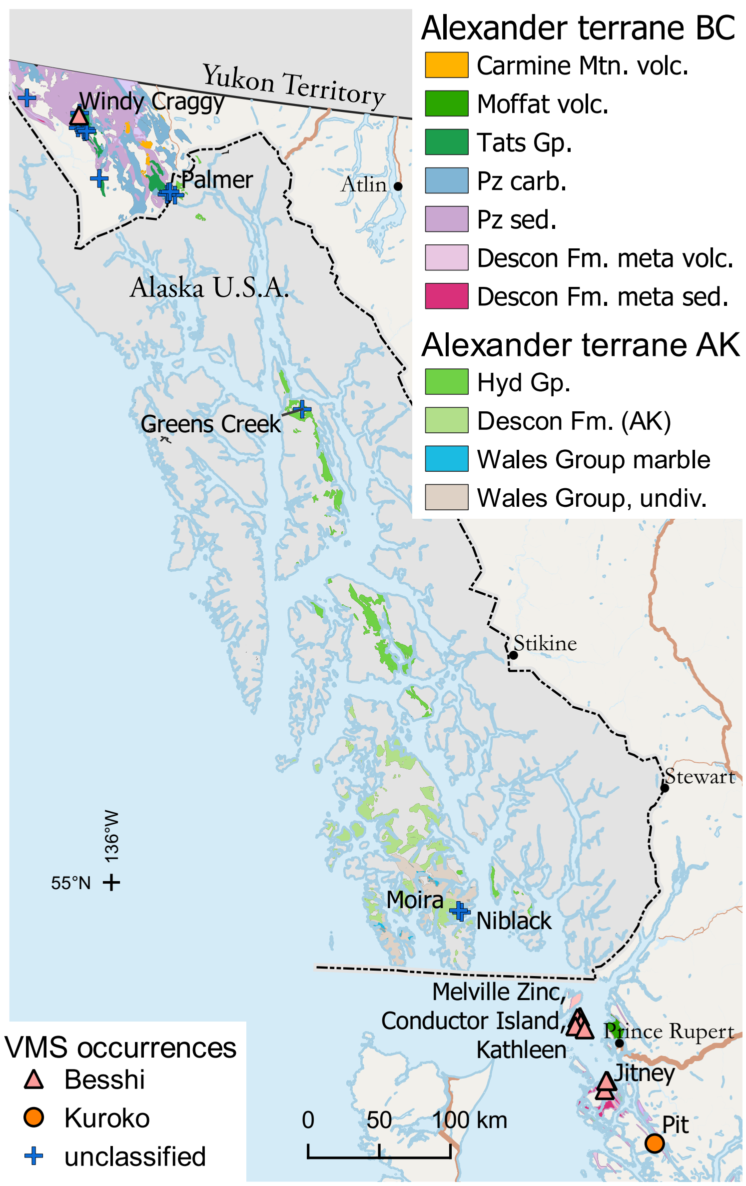

Fig. 18. Alexander terrane VMS deposits. See Figure 2b for location.

on Pitt Island in the southern part of the Alexander terrane (Fig. 18). Nelson et al. (2013b) found lead isotopic ratios comparable to Ordovician volcanogenic deposits of New Brunswick, Newfoundland, Quebec, and Norway and suggested a paleogeographic position of the Alexander terrane near the northern end of the Caledonide chain in the early to mid-Paleozoic. Pit consists of a 3.5 km-long trend of sulphide bodies aligned along a shear zone west of the Grenville Channel fault, which was active in the Cretaceous, although lead isotopic ratios are inconsistent with Cretaceous epigenetic mineralization (Nelson et al., 2013b). To the north, on Porcher, Melville, Conductor, and Dunira Islands, Besshi zinc-copper +/- silver occurrences are at early stages of exploration (Jitney 103J 028, **Kathleen** 3 103J 006, **Melville Zinc** 103J 047, **Conductor Island** 103J 046). Host rocks in most cases are mapped as Descon-correlated Porcher Formation (Lower Ordovician). On Prince of Wales Island in Alaska, targets of probable Ordovician age are also known (e.g., Moira Copper). The Niblack, also on Prince of Wales Island is a more advanced exploration project and a past producer of copper, gold, and silver. Although Nowak et al. (2011) considered mineralization as Neoproterozoic, Karl et al. (2009) dated host rhyolites at 476.7 +/- 1.5 Ma and placed the deposit in the Moira Sound unit, equivalent to the Descon Group.

4.11.2. Tats Group (Late Triassic)

A Late Triassic rift within which the **Windy Craggy** deposit formed (Schulz, 2012) extends southward into southeastern Alaska where it hosts the Glacier Creek deposit and Greens Creek mine in equivalent rocks of the Hyd Group (Fig. 18). Windy Craggy is hosted by mafic flows and sills and underlying predominantly sedimentary units. Greens Creek is also hosted by mafic and siliciclastic rocks but is more zinc-lead-silver-rich than is typical of Besshi deposits. It also lacks felsic volcanic rocks characteristic of Kuroko or many of the Eskay Creek type hybrid VMS-epithermal deposits, leading some to propose a hybrid VMS-SEDEX model (Duke et al., 2010; Taylor et al., 2010).

Windy Craggy (114P 002) is a Besshi copper-cobalt-gold-silver-zinc deposit that has a 1991 historical resource of 300 Mt 1.4% Cu, 0.0690% Co, 3.8 g/t Ag and 0.2 g/t Au. Geddes Resources Ltd. completed stage 1 of the British Columbia Mine Development Assessment Process in 1991, but the review was suspended in 1992. The province created the Tatsenshini-Alsek Provincial Park in 1993, preventing further development. Other, less-developed copper-cobalt bearing occurrences are also in the park.

4.12. Overlap assemblage, Gambier Group (Late Jurassic-Early Cretaceous)

The Gambier Group (and equivalent Fire Lake Group, Brokenback Hill Formation) represents a volcanic arc that formed at the eastern edge of Wrangellia in the Early Cretaceous (Lynch, 1995). It is preserved as pendants in intrusive rocks of the Coast Plutonic Complex and lies unconformably on Lower Jurassic rocks of the Harrison Lake Formation. The Gambier Group is mapped as far as 500 km northwest from the southern end of the Coast Plutonic Complex (Fig. 19; Bellefontaine

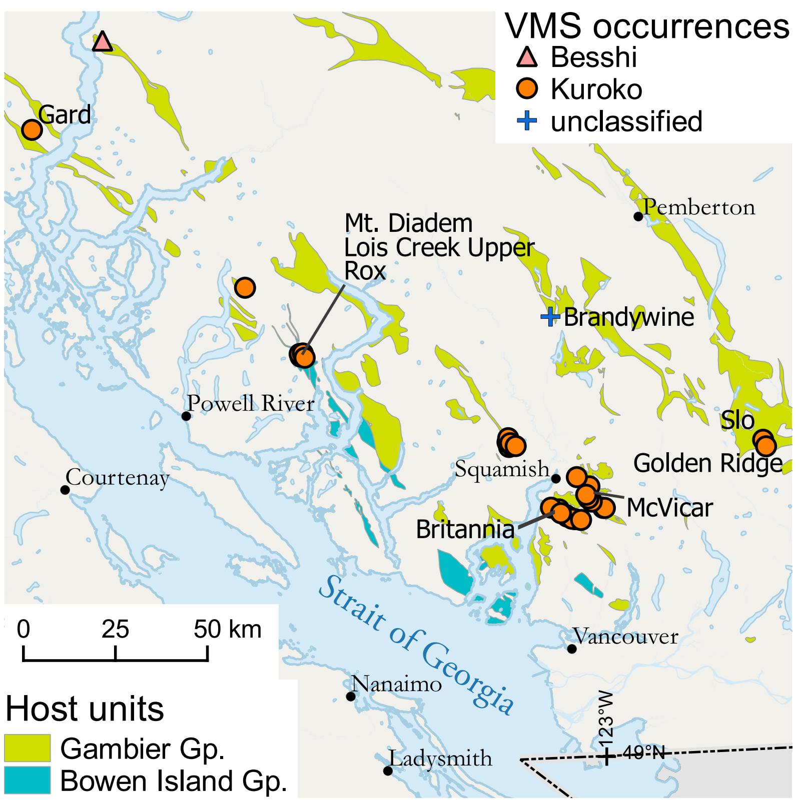

Fig. 19. Gambier Group VMS deposits. See Figure 2b for location.

et al., 1994). The past-producing **Britannia** deposits are in a shear zone in a Gambier Group pendant (Britannia-Indian River pendant. Payne et al., (1980) interpreted the deposits as remobilized volcanogenic massive sulphides originally formed in Lower Cretaceous felsic volcanic rocks. Additional occurrences in the Britannia pendant and in the Gambier Group elsewhere generally resemble the Kuroko model and, considering the productivity of the Britannia deposits, may be underexplored. The Bowen Island Group (Fig. 19), a Lower-Middle Jurassic (Friedman et al., 1990) volcanic unit, hosts a small cluster of Cu-Zn-Pb-Au-Ag polymetallic mineral occurrences.

Britannia (092GNW003) is a Kuroko copper-zinc-lead-silver-gold deposit where 48 Mt were mined from eight zones between 1905 and 1974 at approximately 1.1% Cu, 0.65% Zn, 6.8 g/t Ag and 0.6 g/t Au. At the time of closure, 1.4 Mt reserves remained in No. 10 mine. **McVicar** (092GNW006) is a vein-Kuroko type copper-zinc-lead-silver prospect in the Britannia-Indian River pendant. A 1928 drill program outlined 119,737 tonnes 2% Cu with minor Pb, Zn, Ag. **Brandywine** (092JW 001) is a silver-gold-lead-zinc polymetallic vein occurrence in Gambier Group andesitic and sedimentary rocks. **Golden Ridge** (092GNE038) is a stratabound silver-gold-lead-zinc-copper occurrence in the Fire Lake Group (Lower Cretaceous), in a zone of silicified rhyolite tuff. The Fire Lake Group is part of the series of pendants in the southern Coast Mountains correlative with the Gambier Group (Roddick, 1965; Lynch 1990). **Slo** (092GNE027) is a pyritic showing in the Brokenback Hill Formation with some galena, chalcopyrite, sphalerite and up to 2.65 g/t Au. **Gard** (092K 160) is a Zn-Pb-Cu-Ag-Au showing in a pendant of metavolcanic and metasedimentary rocks correlated with the Gambier Group. **Rox** (092K 083), **Lois Creek Upper** (092K 077), **Mt Diadem** (092K 084) are Zn-Cu-Pb-Ag-Au. The style of mineralization includes veins, shear-hosted pods, and stratabound stringers. Host argillite and volcanic rocks are assigned to the Bowen Island Group.

5. Conclusion

This compilation represents a continuation of the work of Massey (1999), adding further detail on the stratigraphic settings of the main VMS districts in British Columbia, with host units and approximate age. Precious metals enriched VMS and hybrid deposits are currently attractive exploration targets as evidenced by recent exploration at the Eskay Creek and upper Kitsault camps (Clarke et al., 2022). Among predominantly base metals prospects, Kutcho Creek and Yellowhead are advancing through the mine evaluation stage.

As greenfields targets, the small footprint of VMS deposits present an exploration challenge; typically small (Fig 1) tonnages present economic challenges. Environmental risks are highlighted by historical examples such as Britannia and Tulsequah Chief. Nonetheless, most VMS are polymetallic, providing a hedge against price fluctuations of a single commodity. Approximately 60% of VMS occurrences in MINFILE are of the Kuroko type, commonly containing copper, zinc, lead, silver, and gold. Some of these are atypically precious metals enriched, possibly unrecognized or transitional to hybrid type. Occurrences conforming more closely to other VMS models (Besshi, Cyprus) may also be precious metals enriched. It is likely that some historically known occurrences were not thoroughly investigated for minor commodities.

Canada's list of critical minerals (Natural Resources Canada, 2021) includes copper and zinc, two common primary products of VMS deposits. Any significant energy transition from fossil fuels is forecast to require an increased world supply of base metals in addition to metals and minerals with few sources (Kettle and Wlazy, 2021, International Energy Agency, 2021). Some VMS deposits are potential co- or by-product sources of cobalt, manganese, and other metals on the critical list. Gallium, germanium, and indium may be by-products of sphalerite processing, although Ge and Ga are more abundant in lower temperature deposit types (Paradis, 2015). Indium may be elevated in higher temperature deposits like VMS. In rare cases, Ni and Co are significant co-products of VMS type mantle peridotite-related deposits (Outokumpu; Peltonen et al, 2008)

Favourable stratigraphy and VMS-associated rocks have been recognized in, for example, the Alexander, Gambier, Harrison, Stikine, Yukon-Tanana, and Cache Creek terranes, which may have potential that has been overlooked and not yet systematically explored.

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