

Critical minerals and mineral systems in British Columbia



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Abstract

Mining is essential to produce the commodities needed to combat climate change. Low-carbon technologies need critical minerals to produce electric vehicles, mobile phones, solar panels, wind turbines, electrical transmission lines, batteries, and medical devices, and to manufacture products for national defense. Because of global demands, many of these critical minerals are predicted to see shortages, and British Columbia is faced with a generational opportunity for mining that will not only contribute to a low-carbon future but generate significant economic and societal benefits. Already mining critical minerals, British Columbia is Canada's largest producer of Cu, only producer of Mo, mines Mg, and recovers Zn, Ag, and Pb. Adopting a mineral systems approach, the British Columbia Geological Survey is engaging in field, laboratory, and mineral potential modelling studies to evaluate the critical mineral endowment of the province, clarify by- and co-production possibilities of critical minerals not being recovered from current base and precious metal mines, and serve the provincial Critical Minerals Strategy. Six mineral systems are of particular importance: porphyry; volcanogenic massive sulphide; deep-water basin and platformal base-metal; magmatic mafic to ultramafic; carbonatite, and iron skarn. Providing foundational geoscience data and developing novel exploration techniques will encourage discoveries and enhance exploration for underexplored mineral systems. By increasing awareness of critical mineral opportunities for the exploration and mining industries, and by enhancing the critical mineral knowledge base, the province seeks to encourage investment that could lead to new discoveries, expand existing resources, and make British Columbia a significant supplier of the raw materials necessary to address the climate crisis.

Keywords: Critical minerals, critical minerals strategy, mineral criticality, mineral systems, mineral potential modelling, porphyry, volcanogenic massive sulphide, SEDEX, MVT, magmatic mafic to ultramafic, carbonatite, iron skarn

1. Introduction

Critical minerals are essential for low-carbon technologies. These minerals are required for electric vehicles, mobile phones, solar panels, wind turbines, electrical transmission lines, batteries, and medical devices, and to manufacture products for national defense. As society places more value on the transition to low-carbon-based energy, demand for minerals important for energy generation, storage, and transmission will increase. Consequently, jurisdictions around the world are developing strategies to ensure critical mineral supply chains are robust and resilient. In 2021, the Government of Canada released a national critical minerals list (Fig. 1) and the Canadian Critical Minerals Strategy (NRCan, 2022) to encourage investment in critical minerals and strengthen economies while combating climate change. British Columbia, the other provinces, and the territories are also pursuing strategies to take advantage of the global interest in stable and responsible mining jurisdictions.

Mining and mineral exploration contribute greatly to the economy of British Columbia. Employing more than 35,000 people, these industries are particularly important to rural communities. In the last five years, the total value of mining production was \$63.4 billion and the mineral exploration expenditure was \$2.8 billion (Clarke et al., 2020, 2021, 2022, 2023, 2024).

In this paper we first consider how critical minerals are defined, the jurisdictional dependence and transient nature of critical mineral lists and introduce British Columbia's critical minerals atlas. We then describe how the British Columbia Geological Survey has moved away from historical mineral deposit profiles to a more encompassing 'mineral systems' approach, how this approach is applied to modern mineral potential modelling and summarize six mineral systems of importance to critical minerals in British Columbia: porphyry, volcanogenic massive sulphide, deep-water basin and platformal base-metal, magmatic mafic to ultramafic, carbonatite, and iron skarn.

2. Critical minerals and criticality

Although some critical mineral lists do include a small number of minerals or groups of minerals, the term 'critical mineral' is a misnomer because it commonly refers to elements rather than actual minerals. The criticality of minerals is defined by different groups, for different purposes, in different ways, but two criteria are commonly used. First, a mineral may be deemed critical if it serves an essential purpose (e.g., national security or economic health) and second, if it is at risk of supply disruption (e.g., National Research Council, 2008; Graedel et al., 2012; Gunn, 2014; Hayes and McCullough, 2018). Critical mineral lists are neither universal nor static (e.g., Jowitt et al., 2018).

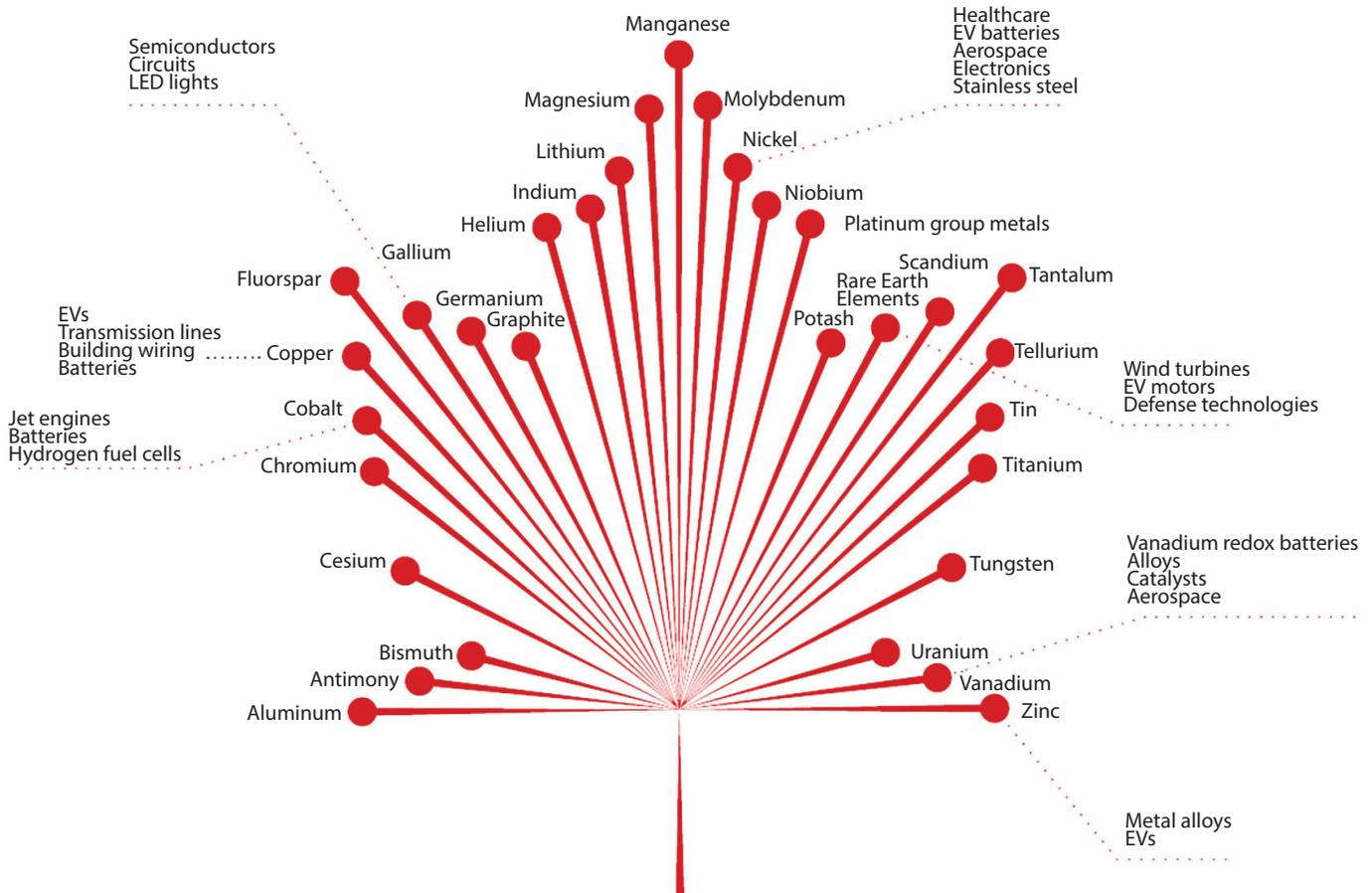


Fig. 1. The 31 critical minerals on the Canadian list and some of their uses. After NRCan (2022).

Based on specific demands and supply vulnerabilities, different countries have different critical minerals lists (e.g., Table 1). Each jurisdiction has variations reflecting supply chain access, geography, and geopolitical circumstance. Critical mineral lists also change with time as demand shifts and technology evolves (e.g., Fortier et al., 2022). Nonetheless, the lists from different jurisdictions have many items in common. From Table 1, more than ten lists include Sb, Bi, Cr, Co, Ga, graphite, In, Li, Mg, Mn, Ni, Nb, platinum group elements (PGE), rare earth elements (REE), Ta, Sn, Ti, W, and V. Five to ten jurisdictions list Al, barite, Be, Cs, Cu, fluorspar, Ge, Hf, He, Mo, P, potash, Rh, Sc, Si, Sr, Te, U, Zn, and Zr. Fewer jurisdictions (less than five) share As, B, Cd, metallurgical coal (coking coal), feldspar, Au, Fe, Pb, Rb, Se, and Ag.

In the last two decades, many organizations have adopted a variation of the United States National Research Council (2008) framework for evaluating the criticality of a material (e.g., Blengini et al., 2020). In general, the criticality framework has two dimensions, one quantifying supply risk, the other economic importance (Fig. 2). For each mineral, risk and economic importance are estimated using proxy indices for different parameters (e.g., Blengini et al., 2020; Nassar et al., 2020). A mineral is deemed critical only if it overcomes user-

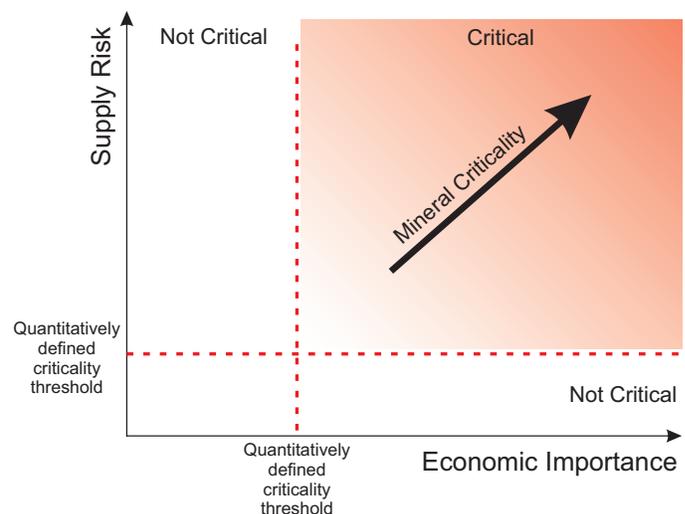


Fig. 2. Two-dimensional criticality framework. Jurisdictions calculate supply risk and economic importance for a mineral then define acceptable thresholds. Minerals with minimal supply risk will not be critical even if of great economic importance. Similarly, minerals of low economic importance will not be critical even if supply risk is high. A combination of both increasing supply risk and economic importance yields increasing criticality. From Hickin et al. (2023).

Table 1. Canadian and key global partner critical mineral lists. Coloured boxes indicate relevance to British Columbia: green are significant; yellow require further evaluation; red are unlikely to be produced. After Hickin et al. (2023).

Minerals	North America							Asia and Australia				Europe		South America	
	USA	CAN	AB	ON	QC	SK	YK	Japan	South Korea	India	AUS	EU	UK	Brazil	Chile
Aluminum/bauxite	x	x	x						x		x	x		x	
Antimony	x	x		x	x		x	x	x	x	x	x	x		
Arsenic	x		x								x	x			
Barite/barium	x		x	x				x				x			x
Beryllium	x			x				x		x	x	x			
Bismuth	x	x	x	x	x		x	x	x	x	x	x	x		
Borate/boron								x				x			
Cadmium					x					x					
Cesium	x	x		x	x			x							
Chromium/chromite	x	x	x	x		x	x	x	x		x				
Cobalt	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Copper		x		x	x	x	x		x	x		x		x	x
Feldspar												x			
Fluorspar/fluorine	x	x		x		x	x	x			x	x			
Gallium	x	x	x	x	x	x	x	x	x	x	x	x	x		
Germanium	x	x	x	x			x	x		x	x	x			
Gold														x	
Graphite/carbon	x	x	x	x	x	x		x	x	x	x	x	x	x	x
Hafnium	x		x					x		x	x	x			
Helium		x	x			x						x			
Indium	x	x	x	x	x		x		x	x	x		x		
Iron														x	
Lead									x						
Lithium	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Magnesium	x	x	x	x	x	x	x	x	x		x	x	x		
Manganese	x	x	x	x		x	x	x	x		x	x		x	x
Metallurgical coal												x			
Molybdenum		x		x		x	x	x	x	x	x			x	x
Nickel	x	x	x	x	x	x	x	x	x	x		x		x	
Niobium	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
PGE	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Phosphate/phosphorous	x			x						x		x		x	
Potash		x	x			x				x				x	
REE	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rhenium								x		x	x				x
Rubidium	x							x							
Scandium	x	x	x	x	x	x				x	x	x			
Selenium				x				x	x	x	x				
Silica/silicon								x	x	x	x	x	x	x	
Silver															
Strontium								x	x	x		x			
Tantalum	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Tellurium	x	x		x	x		x	x		x	x		x		
Tin	x	x	x	x	x	x	x		x	x			x	x	
Titanium	x	x	x	x	x	x	x	x	x	x	x	x		x	x
Tungsten	x	x		x		x	x	x	x	x	x	x	x	x	x
Uranium	x	x	x	x		x	x							x	
Vanadium	x	x	x	x	x		x	x	x	x	x	x	x	x	x
Zinc	x	x	x	x	x	x	x		x						x
Zirconium	x		x	x				x	x	x	x				

defined thresholds in supply risk and economic importance. The Government of Canada has taken a criteria-based approach in developing the national critical mineral list (Gadd et al., 2022a). The criteria, which were established in consultation with the provinces, territories, and industry representatives, specify that the critical mineral must be: 1) essential to Canada's economic security; 2) required for Canada's transition to a low-carbon economy; and/or 3) a sustainable source for partner nations. The current list (Fig. 1) consists of 31 critical minerals including 27 elements, two groups of elements (platinum group elements and rare earth elements), and two minerals (fluorspar, potash).

3. British Columbia's critical mineral atlas

British Columbia is developing its own Critical Minerals Strategy and BCGS has compiled a critical minerals atlas as the initial step in evaluating the critical mineral endowment of the province and in building awareness of critical mineral opportunities for the exploration and mining industries (Hickin et al., 2023). The atlas is not British Columbia's official critical mineral list. Instead, it represents an inventory of commodities in the province that appear on the Canadian list or on those of key trading partners (Table 1). Acknowledging that many are unlikely to appear on the final critical minerals list for British Columbia, 41 elements/minerals are detailed. Each is presented on a data sheet that provides descriptions, mineral properties, uses and importance, global production, modes of occurrence, and overviews of occurrences in British Columbia. A map is included with each data sheet depicting the distribution of known occurrences in British Columbia and shows the status of each occurrence (current producer, past producer, developed prospect, prospect, showing). Where available, current, past production, and mineral resource data are tabulated.

4. From mineral deposit profiles to mineral systems

The British Columbia Geological Survey has mapped and inventoried the mineral deposits of the province for more than 130 years (Sutherland Brown, 1998). More than 30 years ago, the Survey initiated a study to assess the mineral potential of the entire province. This pioneering work combined known mineral occurrences, what was then understood about which rocks favour mineral deposition, and the geology of a given area to develop a relative ranking of mineral potential (Kilby, 1995, 2004; Grunsky, 1997; MacIntyre and Kilby, 2009). Emphasizing the differences between deposit types, mineral potential assessments focused on deposit profiles that classified occurrences into about 120 deposit types based mainly on genetic models (e.g., Lefebvre and Jones, 2022). The profiles included descriptions of geological characteristics, mineral exploration techniques, resource data, age of mineralization, tectonic setting, and concepts about deposit origins. The approach used built on work by the United States Geological Survey (Brew, 1992; Singer, 1993) but modified for British Columbia (Kilby, 2004). Tracts of land of similar geological character were defined and experts from government, industry, and

academia assessed all available data to determine probabilistic estimates for the expected number of undiscovered deposits. The ranking of the land base for metallic deposits was based on the gross in-place value of the commodities for both known and estimated undiscovered deposits. The dollar value of each tract was determined using expert input, commodity prices, and a Monte Carlo simulation to determine probable tonnage and grade information for each deposit type. Importantly, the dollar scores were intended as a ranking tool and not intended to imply a particular dollar value to the ground being ranked. These mineral potential data remain a valuable contribution for land use assessment, but do not provide commodity-specific information.

To support current land-use decisions and evaluate critical mineral opportunities, the Survey is now reviving provincial mineral potential assessment (Wearmouth et al., 2024). In contrast to previous approaches, which emphasized the differences between deposits split into about 120 types, the current assessment adopts a mineral system approach, which emphasizes similarities between deposits and uses a large-scale view of all the factors that control generating and preserving deposits (e.g., Knox-Robinson and Wyborn, 1997; Hronsky and Groves, 2008; McCuaig et al., 2010; Ford et al., 2019; Groves et al., 2022). Originally proposed by Wyborn et al. (1994) and drawing on ideas from the petroleum industry (e.g., Magoon and Dow, 1994), each mineral system includes an ore source and driving force, a transport mechanism and pathway, and a physical or chemical trap (Knox-Robinson and Wyborn, 1997). The approach recognizes that the ore deposit, which is relatively small (<1 km in plan view), is the central feature of a larger system that may be detectable at a regional scale (>10 km in plan view). Being process-based, the mineral systems approach is neither restricted to a geological setting nor limited to a specific ore deposit type. The mineral systems approach focuses on processes that are common across mineral systems, which enables the simultaneous assessment of many deposit types at a variety of scales (McCuaig et al., 2010).

5. Six important mineral systems in British Columbia

Gadd et al. (2022a) highlighted important mineral systems in Canada of significance for precious and base metals and critical minerals. Following a similar approach, below we summarize selected mineral systems that are important to British Columbia and the ongoing Survey research directed at better understanding mineral potential and critical mineral opportunities.

The mineral endowment of British Columbia and the tectonic evolution of the Canadian Cordillera are intimately linked. The Canadian Cordillera records a history of supercontinent rifting and a succession of island arc volcanosedimentary and intrusive assemblages (terranes) developed outboard of Ancestral North America and accreted to each other and to the proto-continental margin with final amalgamation produced by collisions driven by the westward motion of the North American continental plate. The amalgamated Cordillera then

became the site of Cretaceous and Cenozoic arc and post-arc magmatism. Terrane evolution continues today as the Juan de Fuca plate slides beneath Vancouver Island (Fig. 3). As reviewed by Nelson et al. (2013a), Hickin et al. (2017) and Colpron and Nelson (2021), the diverse tectonic processes, from supercontinent breakup through development of long-lived arc terranes, to terrane accretion and post-accretion magmatism, metamorphism, deformation, and sedimentation, have generated diverse mineral systems across the province.

present-day Cascadia subduction zone and Queen Charlotte fault. Modern-day volcanic complexes related to Cascadia subduction are distributed along the length of the western Cordillera, and many of the terranes are partially covered by sedimentary rocks that were deposited during terrane accretion and collision, when older rocks were deformed, uplifted, eroded, and redeposited in newly created sedimentary basins. The variety of tectonic settings and paleogeographic environments recorded by these terranes and superterranes

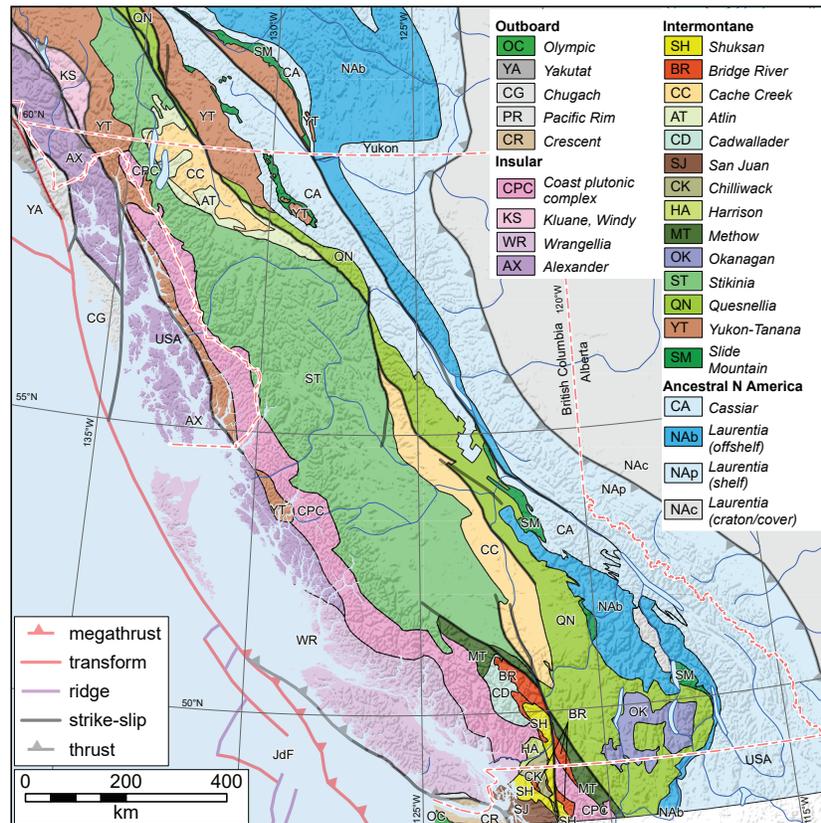


Fig. 3. Superterranes, terranes, and modern tectonic elements of the Canadian Cordillera in British Columbia. Modified after Colpron (2020).

West of Ancestral North America, Cordilleran terranes are commonly grouped into superterranes and terranes (Fig. 3). Ancestral North America consists of predominantly sedimentary rocks that were deposited on cratonic basement during the Paleoproterozoic and Mesoproterozoic and during and after the Neoproterozoic to Cambrian breakup of the supercontinent Rodinia, which created the western margin of Laurentia, the nucleus of what is now North America. The Intermontane superterrane consists of a diverse group of Late Paleozoic to Mesozoic volcano-sedimentary assemblages and kindred intrusive bodies that formed mainly in and adjacent to island arcs outboard of Ancestral North America in the proto-Pacific Ocean. The Insular superterrane consists of similar island arc terranes; the Intermontane-Insular terrane boundary lies within the syn- to post-accretionary Coast Plutonic complex, a linear arc-axial belt that extends the length of the Cordillera. The Outboard terranes are mostly late Mesozoic to Cenozoic forearc siliciclastic assemblages, bounded to the west by the

since the Mesoproterozoic generated conditions favourable for a variety of mineral systems.

5.1. Porphyry systems

Porphyry deposits are the world's largest source of Cu and Mo and individually can contain 100s of millions to billions of metric tons of ore. These deposits typically form above subduction zones at convergent plate margins associated with calc-alkaline volcano-plutonic arcs but can also form from alkaline magmas in post-subduction settings, such as has been inferred in British Columbia, particularly in Quesnel and Stikine terranes (Fig. 4; Nelson et al., 2013a; Logan and Mihalynuk, 2014; Hickin et al., 2017; Colpron and Nelson, 2021). Of the eleven mines that operated in British Columbia in 2023, seven are porphyry deposits. The province is the largest Canadian producer of copper (typically 40-50%) and only producer of molybdenum (Clarke et al., 2024), both of which are on the national critical minerals list (NRCan, 2022). Porphyry deposits have numerous

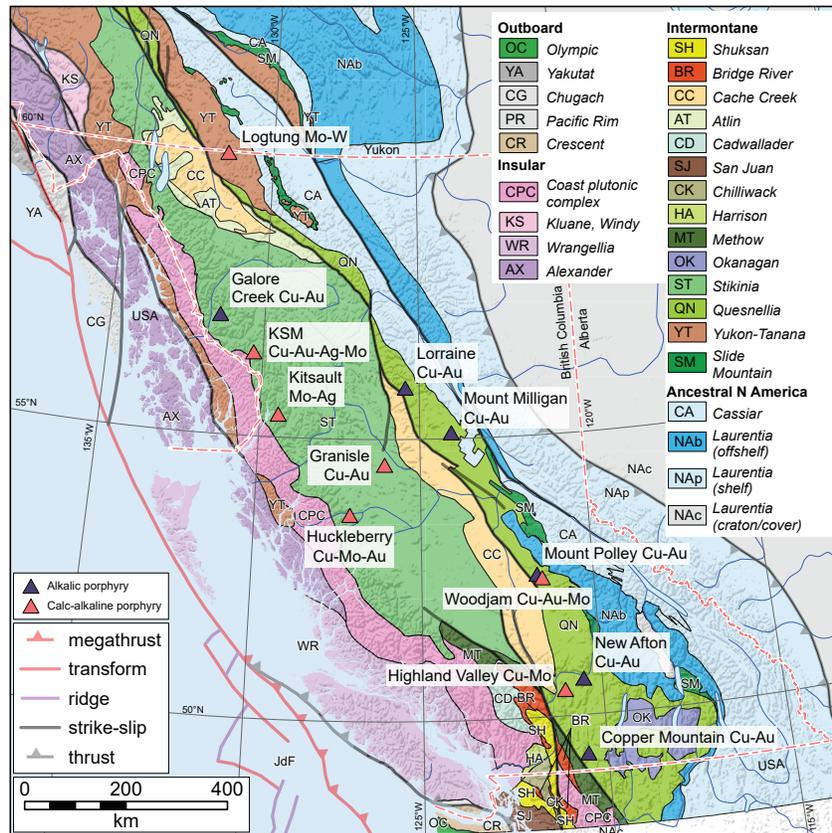


Fig. 4. Selected porphyry deposits in British Columbia. Terranes after Colpron (2020).

subtypes grouped under the broad class referred to as ‘porphyry (D)’ by Lefebvre and Jones (2022), and porphyry systems may also include other types such as skarn, carbonate replacement, and high- and intermediate-sulphidation epithermal deposits (Fig. 5; e.g., Sillitoe, 2010; Orovan and Hollings, 2020). In porphyry systems, hydrothermal fluids interact with surrounding rocks creating characteristic and predictable alteration assemblages (Fig. 5). In the green rock environment, an extensive and zoned alteration halo surrounds the potassic (K-feldspar-biotite-chalcopyrite) core centered on a porphyritic intrusive complex (Sillitoe, 2010; Orovan and Hollings, 2020). Immediately outwards from the potassic core is the inner propylitic subzone (or actinolite subzone), which is defined by the occurrence of actinolite. Other minerals in this assemblage may include combinations of albite, epidote, chlorite, calcite, hematite, magnetite, and pyrite. The medial propylitic zone is the epidote subzone; it has a similar mineral assemblage but lacks actinolite. The outermost propylitic zone is the chlorite subzone, which lacks actinolite, epidote, and commonly magnetite. This alteration zonation reflects the decreasing fluid temperature outward from a central heat source, providing a distinctive and observable guide to potential mineralization (Cooke et al., 2014; Orovan et al., 2018; Pacey et al., 2020; Orovan and Hollings, 2020). The green rock alteration domains may be subjacent to or overprinted by a lithocap, its feeder structures, or other late-stage upward-flaring alteration

features, which may include advanced argillic (quartz-alunite-clay), silicic (quartz), argillic (clay), phyllic/sericitic (quartz-sericite-pyrite), and intermediate argillic (sericite-clay-chlorite) alteration zones. High-sulphidation epithermal mineralization may be embedded in the lithocap environment, containing a combination of pyrite, enargite, covellite-digenite, chalcopyrite and tetrahedrite/tennantite. Sodic-calcic alteration (albite-epidote-chlorite-actinolite) may be present in a deep or medial position with respect to the mineralizing porphyritic intrusive complex, where it overprints potassic and/or propylitic alteration. Where reactive host-rock horizons are present, skarn alteration assemblages and mineralization may develop, consisting of Cu-rich minerals close to the intrusion, and more Zn-Pb-rich mineralization farther out. Within zones of high-angle normal faults or breccias that are medial to distal to the porphyritic intrusive complex, intermediate-sulphidation mineralization may form consisting of base metal sulphides, including silver-bearing tetrahedrite, electrum, chalcopyrite, barite, galena, and sphalerite. This mineralization typically occurs with quartz-adularia-illite-pyrite alteration.

The main commodity of economic interest in porphyry deposits is Cu, with Mo and Au common co-products and Ag the most common by-product. Porphyry Mo deposits typically lack co-products, although W or Ag have been reported (e.g., Kitsault Mo-Ag, Fig. 4; Steininger, 1985). The most noted by-products recovered from porphyry deposits include Ag, As,

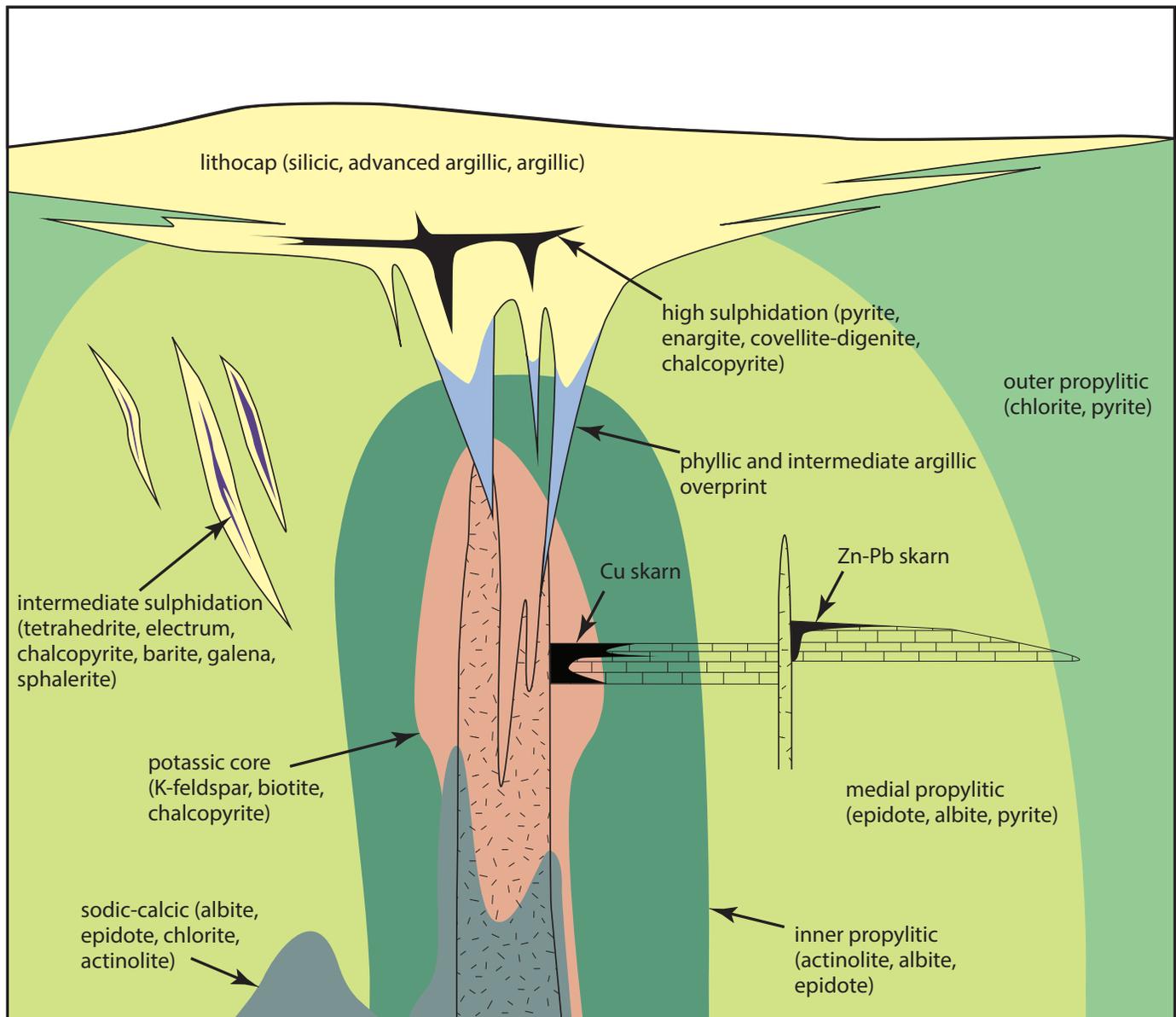


Fig. 5. Diagram of typical alteration zonation patterns and overprinting relationships in the porphyry environment. The green rock environment includes three subfacies of propylitic alteration that are zoned about an intrusive complex and proximal associated potassic alteration. The propylitic alteration passes outward from an inner high-temperature subzone characterized by the presence of actinolite to an intermediate-temperature subzone containing epidote to an outer low-temperature subzone with predominantly chlorite. Upward-flaring zones of phyllic (sericitic) and/or intermediate argillic (sericite-clay-chlorite) alteration may overprint the upper portions of the porphyry system and may transition into a lithocap (including silicic, advanced argillic, and argillic alteration) at shallow levels. The lithocap can host high-sulphidation epithermal mineralization. At deeper levels (or medial to the mineralizing intrusions) sodic-calcic alteration may overprint the potassic core and/or propylitic halo. Where reactive host-rock horizons are present, skarn alteration assemblages and mineralization may develop. Medial to distal fault intersections or breccia zones may host intermediate-sulphidation epithermal mineralization. Modified after Cooke et al. (2020).

PGE, Re, Se, Te, W, Sn, U, Zn, monazite, silica, and sulphuric acid (Sillitoe, 1983; John and Taylor, 2016). Additionally, Be and Bi can be enriched in porphyry Mo deposits (e.g., 1 cm-long beryl crystals and bismuthinite at the Logtung porphyry Mo-W deposit, (Fig. 4; Noble et al., 1995; Mihalyuk and Heaman, 2002). Other metals that may be enriched include Nb, In, Cs, F, Li, Rb, Ta, Co and REE but rarely in concentrations that are of economic interest (John and Taylor, 2016; Velasquez et al., 2020). Gold and Ag are the major commodities in porphyry-

related epithermal deposits; Pb, Zn and Hg are common co-products in intermediate-sulphidation deposits, whereas Cu is the most common co-product in high-sulphidation deposits.

Porphyry deposits are typically found in hydrous, oxidized, shallow-level intrusive rocks formed above subduction zones (Fig. 6), but can also occur in post-subduction and post-collision or extensional back-arc settings. Most magmatic rocks in these settings lack porphyry deposits, suggesting that a particular sequence of ore-forming conditions must be met (e.g., Park et

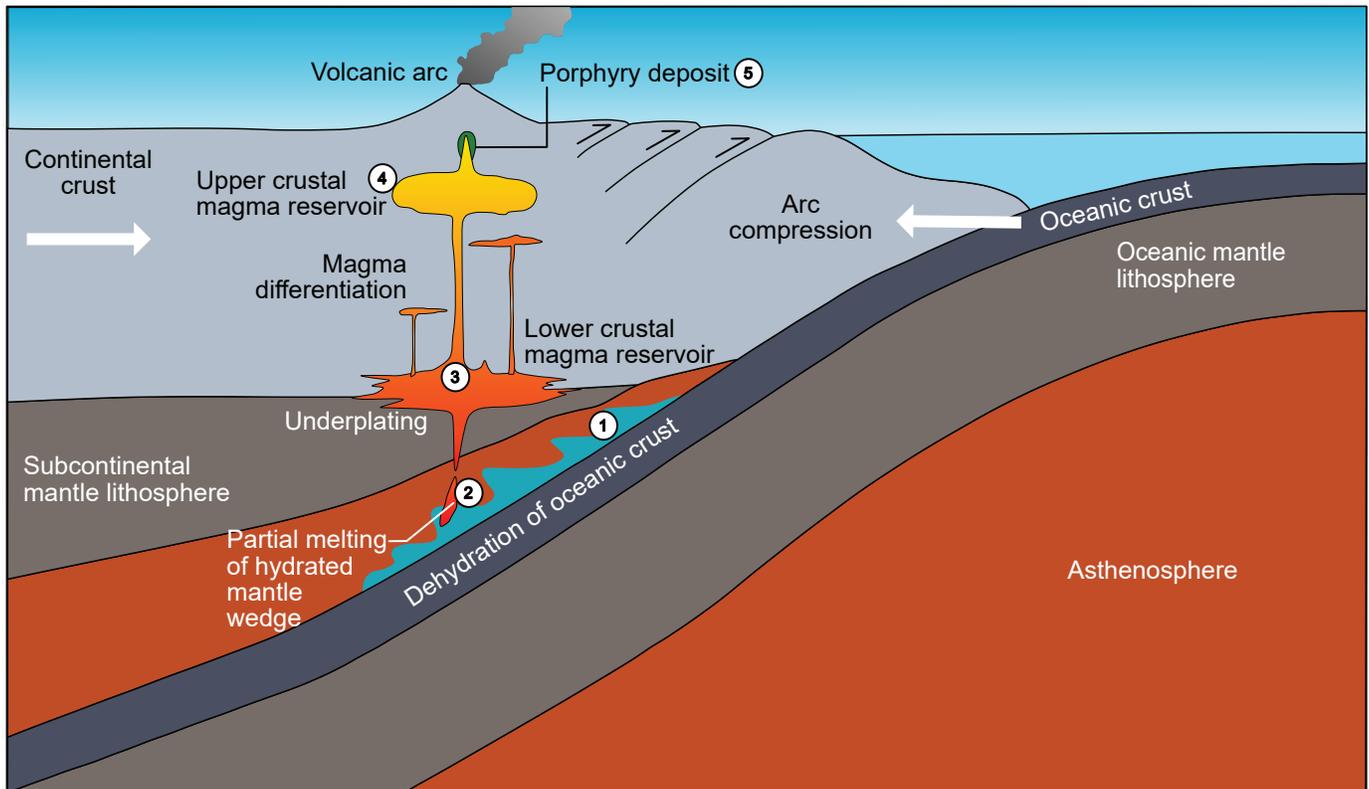


Fig. 6. Tectonic and magmatic conditions to form porphyry deposits. **1)** In a subduction zone, an oceanic plate consisting of hydrated sediments and altered oceanic crust is dragged downward toward the mantle. Fluids and hydrous melts are released from this subducting slab causing hydration of the overlying mantle wedge. **2)** Hydration of the mantle wedge results in flux melting of mantle peridotite, producing oxidized, hydrous basaltic arc magma reservoirs in the mid to lower crust (~30-70 km depth). **3)** The arc magma differentiates by fractional crystallization, crustal assimilation, recharge and mixing. **4)** The evolved magma rises to form an upper crustal magma chamber (~5-15 km depth). **5)** The melt intrudes into the shallow crust at depths of 1-7 km, forming porphyritic intrusions that exsolve Cu-rich ore fluids that form porphyry deposits. Modified after Park et al. (2021).

al., 2021). Several processes contribute to creating porphyry deposits, although workers may disagree on their relative importance (Fig. 6). First, fluids and hydrous melts are liberated from a subducting slab. Second, the mantle wedge is hydrated causing flux melting of mantle peridotite and the production of oxidized, hydrous basaltic arc magma, which ascends and pools in deep reservoirs in the mid to lower crust (~30-70 km depth; Richards, 2011). Magma in these deep reservoirs then differentiates by fractional crystallization, crustal assimilation, recharge, and mixing (Lee and Tang, 2020). This evolved magma then rises to the upper crust (~5-15 km depth) becoming fluid-saturated due to fractional crystallization and low H_2O solubility at low pressure (Chiaradia and Caricchi, 2017). Finally, the fluid-saturated melt intrudes into the shallow crust at depths of 1-7 km, forming pencil-shaped plugs, stocks, and dikes that exsolve fluids forming a hydrothermal circulation system precipitating metal-rich sulphide minerals (Sillitoe, 2010).

Although there are Late Neogene and Jurassic examples in Wrangell terrane on Vancouver Island (Nixon et al., 2020a), most porphyry deposits are in the interior of the province, in Triassic to Jurassic volcanoplutonic rocks of Quesnel and Stikine terranes (Fig. 4; e.g., Logan and Mihalynuk, 2014).

These deposits can be subdivided geochemically and by their metal endowment. Calc-alkaline porphyry deposits, the most common variety, include Cu, Mo, Cu-Mo, and Cu-Au systems (e.g., Highland Valley, KSM, Woodjam). Alkalic porphyry deposits are restricted to Cu-Au systems and are Late Triassic to Early Jurassic, and locally contain PGE (e.g., Copper Mountain, New Afton, Lorraine). The alkalic porphyry Cu-Au deposits can be associated with breccia complexes (e.g., Mt. Polley), silica-undersaturated alkalic intrusions (e.g., Galore Creek), or silica-saturated alkalic intrusions (e.g., Mount Milligan). The plutons that host Quesnel terrane deposits conform, in part, to a pattern defined by parallel belts of calc-alkaline and alkalic plutons that become progressively younger from west to east (Logan and Mihalynuk, 2014; Schiarizza, 2014). Logan and Mihalynuk (2014) emphasized that a narrow 15-m.y. time interval spanning the Jurassic-Triassic boundary, particularly a 6 m.y. pulse centred at 205 Ma, was a particularly prolific episode during which most of the mineralization took place. However, significant porphyry deposits also formed in Stikine terrane during the Cretaceous (e.g., Huckleberry) and Eocene (e.g., Granisle, Kitsault).

Because of their importance to the economy of British Columbia, porphyry deposits have been studied by Survey

geologists for many decades, a tradition that continues today. In the last ten years, integrated field and laboratory studies have been dedicated toward unravelling the tectonic and metallogenic evolution of the main porphyry-bearing terranes of Stikinia (e.g., Nelson and Kyba, 2014; Barresi et al., 2015; Mihalynuk et al., 2016; van Straaten and Nelson, 2016; van Straaten and Gibson, 2017; Febbo et al., 2019; Ootes et al., 2020; Stanley and Nelson, 2022; van der Vlugt, 2022; van Straaten et al., 2022, 2023; Jones et al., 2023; Norris et al., 2023; van Straaten, 2024) and Quesnellia (e.g., Logan and Mihalynuk, 2013, 2014; Mihalynuk and Logan, 2013a, b; Logan and Schiarizza, 2014; Schiarizza, 2015; Mihalynuk and Diakow, 2020; Schiarizza and Friedman, 2021). Recent publications by Logan et al. (2020), Nelson and van Straaten (2020), Colpron and Nelson (2021), and Nelson et al. (2022) synthesize some of this work, and recent dedicated volumes edited by Sharman et al. (2020) and Plouffe and Schetselaar (2021) provide additional province-wide and detailed studies. Particularly important has been the development of new tectonic models about the transition from the Stuhini arc to the Hazelton arc in Stikinia, a transition of arc reorganization with major metallogenic significance (Nelson et al., 2022) and the important role that long-lived, deep-level structural corridors have for generating porphyry deposits in Stikinia and perhaps elsewhere (Nelson and van Straaten, 2020).

Given the thick and extensive drift cover across many areas, considerable attention has also been devoted to examining the down-ice dispersal of material derived from hidden porphyry deposits using samples from subglacial tills, which typically represent the first derivative from bedrock. These studies include province-wide ice-flow compilations (Arnold and Ferbey, 2020), basal till potential maps (e.g. Ferbey, 2014), examinations of porphyry deposit indicator minerals (e.g., Ferbey et al., 2016, 2018; Canil et al., 2017; Lian and Hickin, 2017; Plouffe and Ferbey, 2017, 2019; Mao et al., 2017; Bustard et al., 2019; Lee et al., 2021; Plouffe et al., 2021), and using remotely piloted aircraft systems (drones) to collect lidar, radiometric, and magnetic data (e.g., Ferbey and Elia, 2021; Elia et al., 2023, 2024; Ferbey et al., 2024). Current work includes characterizing the petrogenesis and critical mineral deportment across alteration assemblages and delineating co- and by-products across the spectrum of porphyry deposit subtypes in the province, starting with the historical Kitsault Mo-Ag mine (Orovan et al., 2024).

5.2. Volcanogenic massive sulphide systems (VMS)

Volcanogenic massive sulphide (VMS) deposits are accumulations of sulphide minerals precipitated at sites of rift-related submarine volcanism on the floors of modern and ancient seas. The deposits form where hot metal-rich magmatic fluids rise, discharge, and mix with seawater (e.g., Lydon, 1984, 1988; Franklin et al., 2005; Galley et al., 2007; Cousens and Piercey, 2008; Hannington et al., 2011; Piercey, 2011; Ross and Mercier-Langevin, 2014). Based on volcanic rock type(s) typically related to tectonic setting, VMS deposits have been

subdivided into numerous categories named after type localities included in the “marine volcanic association” of Lefebvre and Jones (2022; see Northcote, 2022 for review). The primary metals in VMS systems are Cu and Zn, with secondary Pb. More rarely, VMS systems contain Co (e.g., Windy-Craggy, in British Columbia; Fig. 7; Peter and Scott, 1999; Leybourne et al., 2022), or are rich in Au and Ag (Eskay Creek in British Columbia; Sherlock et al., 1999; Mercier-Langevin et al., 2011). By-products from VMS production may include Au and Ag, and some deposits have a host of other critical metals (e.g., Bi, Co, Ga, Ge, In, Sb, Sn, Te, Tl; Paradis, 2015; Leybourne et al., 2022).

Volcanogenic massive sulphide deposits form in extensional tectonic settings where new sea floor is being created, such as at mid-oceanic ridges (MOR), rifting-arcs, and back-arc basins (Fig. 8; Lentz, 1998; Franklin et al., 2005; Galley et al., 2007; Cousens and Piercey, 2008; Piercey, 2011). Although many modern mid-ocean ridge examples have been documented, ancient examples are rare because thin, juvenile oceanic crust is easily subducted. Rifting arcs and back-arc basins have a higher preservation potential and are the tectonic settings most represented in the rock record.

Observations of modern seafloor processes have provided direct information on the origin of VMS, making this deposit class one of the best studied and understood mineralizing systems (Fig. 9; e.g., Lydon, 1984, 1988; Franklin et al., 2005; Galley et al., 2007). Driven by magmatic heat, oceanic water circulates through seafloor volcanic and sedimentary deposits as hydrothermal fluids. These fluids scavenge metals and are focused and discharged through hydrothermal vents called black smokers, precipitating the metals as sulphide complexes within vents and adjacent aprons (Franklin et al., 2005; Galley et al., 2007). In some deposits, syn-volcanic intrusions are the source of metals (e.g., Leybourne et al., 2022), and some deposits form during sub-seafloor replacement processes (Doyle and Allen, 2003; Piercey, 2015). Intervals of volcanic quiescence are required to establish significant massive sulphide accumulations undiluted by large volumes of volcanic rock. Ancient deposits are likely deformed and/or metamorphosed. Although the genetic model for VMS formation generally applies, the geometry of the mineralization, alteration envelope, and host-rocks may be significantly and unpredictably modified, and the search for potential VMS deposits in deformed terranes requires a combination of detailed structural and lithofacies mapping (e.g., Lafrance et al., 2020).

Key features of VMS deposits (Fig. 9) include: 1) occurrence in seafloor volcanic and sedimentary rocks; 2) spatial relationship to syn-volcanic caldera complexes, which are recognized by lateral facies changes, such as transitions away from plateau flows to escarpments to escarpment-related breccia aprons; 3) proximity to syn-volcanic intrusions, which act as heat pumps for circulating hydrothermal fluids; 4) textural preservation of primary volcanic rock-forming minerals albeit altered by interactions with hydrothermal fluids; 5) accumulations of sulphide minerals, typically

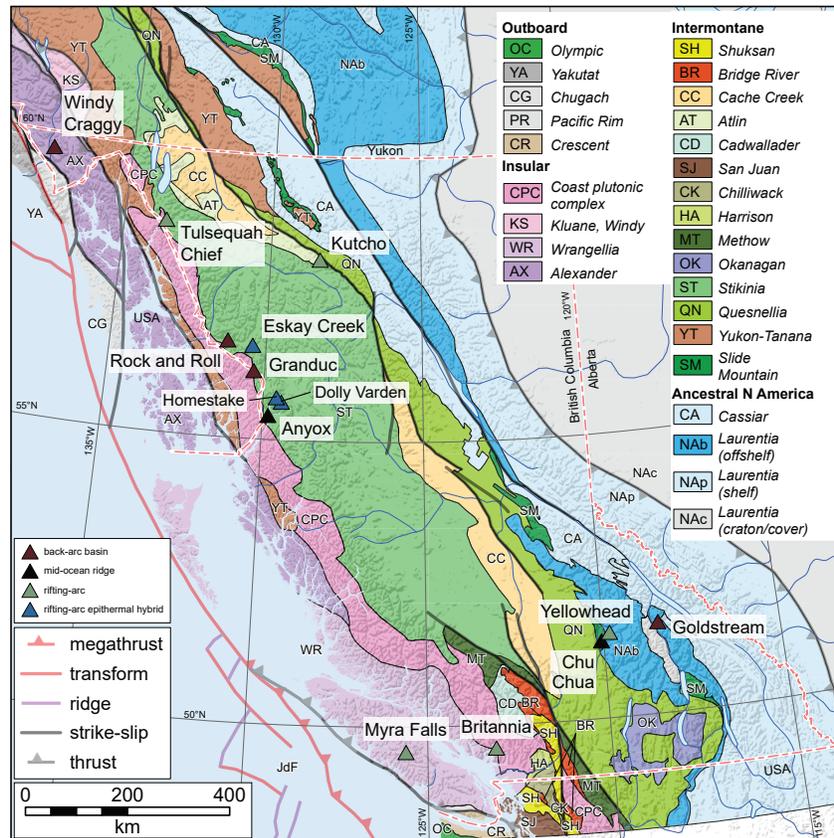


Fig. 7. Selected volcanogenic massive sulphide deposits in British Columbia (see Northcote, 2022 for review). Terranes after Colpron (2020).

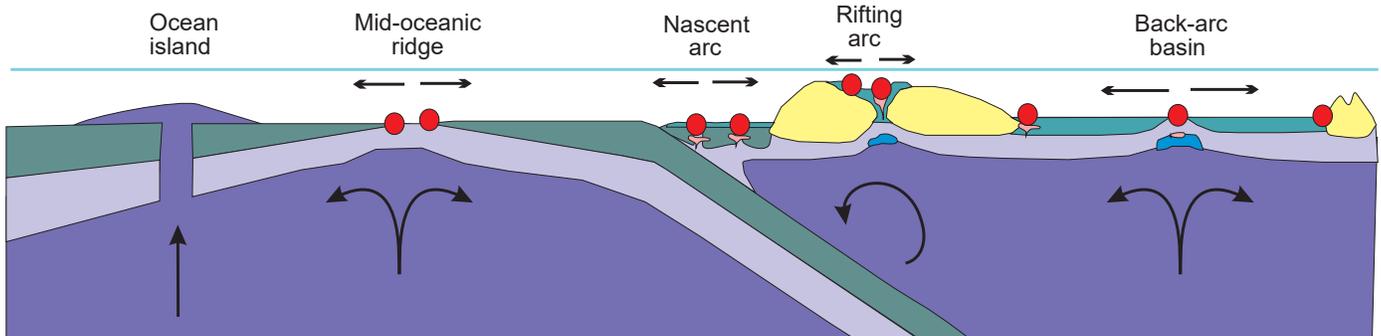


Fig. 8. Tectonic settings of volcanogenic massive sulphide (VMS) deposits (red circles).

chalcopyrite and sphalerite (\pm galena), pyrite, and pyrrhotite, in hydrothermal vent complexes; 6) additional replacement mineralization in vent and apron environments; and 7) lateral transitions to exhalative deposits such as those similar to banded iron formations that may have elevated Zn, Mn, or Ba. Key starting points for recognizing environments with potential for VMS mineralization include deep-water volcanic rocks with abrupt facies changes, alteration of primary compositions (e.g., bleaching, epidote-rich cores to pillowed basalts), and potential syn-volcanic intrusions (Campbell et al., 1981; Hannington et al., 2003; Franklin et al., 2005; Galley et al., 2007; Cousens and Piercey, 2008; Piercey, 2011).

VMS and vent-proximal SEDEX deposits (see section 5.3.) form in similar ways, but there are a few key differences. First, VMS deposits are mainly hosted by volcanic rocks, whereas SEDEX deposits are hosted by deep-water sedimentary rocks with only sparse volcanic rocks. Second, syn-volcanic intrusions are common in VMS deposits but not in SEDEX deposits. Third, alteration of host-rocks near VMS deposits is extensive and can be used as an exploration tool, whereas alteration in SEDEX host rocks is not significant. Fourth, VMS mineralization is predominantly Cu-Zn (\pm Pb, Au, Ag), whereas SEDEX deposits contain Zn-Pb (\pm Ba) with little to no Cu.

Most VMS occurrences in British Columbia are rifting arc-

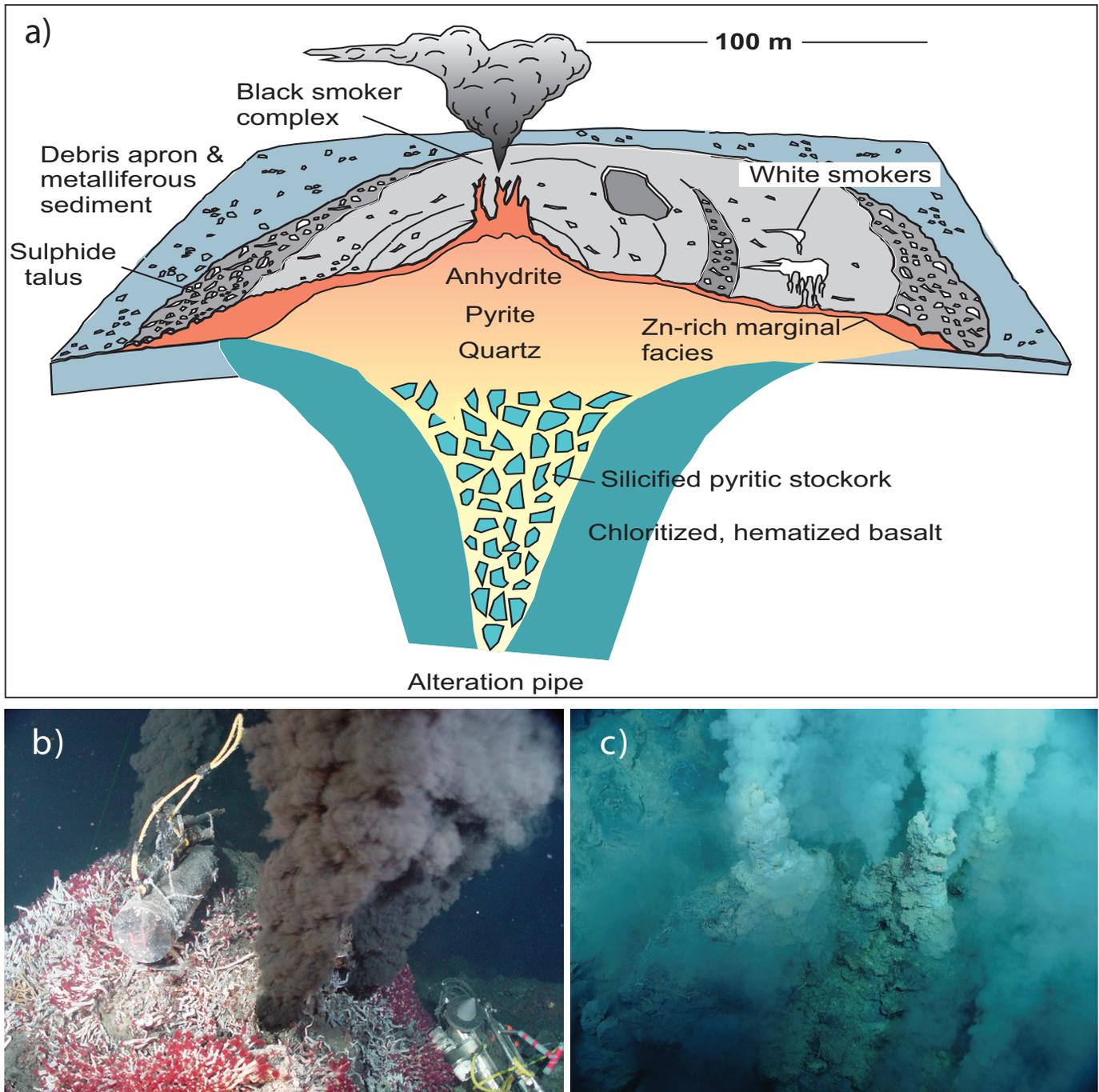


Fig. 9. a) Schematic diagram of a modern hydrothermal chimney complex discharging metal-rich hydrothermal fluids on the seafloor. Modified after Galley et al. (2007) and references therein. b) Black smoker venting metal-rich hydrothermal fluids and precipitating fine-grained sulphide minerals on the seafloor (United States National Oceanic and Atmospheric Administration). c) Lower temperature white smoker venting carbonate- and sulphate-rich minerals on the sea floor (United States National Oceanic and Atmospheric Administration).

related Zn-Pb-Cu-Ag-Au deposits including the currently producing Myra Falls mine and past-producing Britannia and Tulsequah Chief mines (Fig. 7). However, precious metals-enriched rifting-arc VMS and epithermal hybrid deposits are also high priority targets. The high-grade Eskay Creek deposit, in volcanic and sedimentary rocks filling the narrow north-trending, fault-bounded Eskay rift, exemplifies this

type. East of the Eskay rift but with a slightly older inferred time of deposition, mineralization at the Dolly Varden and Homestake deposits also has characteristics of both VMS and epithermal vein and open-space filling styles (Hunter et al., 2022; Turner and Hough, 2023). The combined Homestake and Dolly Varden deposits contain a 4.153 Mt Indicated resource of 34.731 Moz Ag, 166.0 koz Au, 2.87 Mlb Cu, and

1.25 Mlb Pb and an additional 6.831 Mt Inferred resource containing 29.3 Moz Ag and 817 koz Au (Turner and Hough, 2023). The Kutcho Creek rifting arc deposits are hosted by primitive arc volcanic and volcanoclastic rocks of the Kutcho assemblage (Permian-Triassic; Schiarizza, 2012). Orebodies are in a sequence of lapilli, crystal-lithic, and quartz-feldspar crystal tuffs. The feasibility stage project has a combined Measured and Indicated 22.8 Mt grading 1.52% Cu, 2.18% Zn, 28.1 g/t Ag, and 0.39 g/t Au. The Inferred resource is 12.9 Mt grading 1.10% Cu, 1.58% Zn, 20.0 g/t Ag, and 0.25 g/t Au (CSA Global Mining Industry Consultants Canada Limited, 2021). The feasibility-stage Yellowhead deposit is also a rifting arc VMS (Höy, 1997), hosted in metavolcanic and metasedimentary rocks of the Upper Eagle Bay assemblage (Devonian-Lower Mississippian). The deposit is remobilized but remains generally conformable with host rock stratigraphy. Total potentially bulk mineable resources are estimated at 1292 Mt grading 0.25% Cu, 0.028 g/t Au, and 1.2 g/t Ag Measured and Indicated and 109 Mt grading 0.21% Cu, 0.024 g/t Au, and 1.2 g/t Ag Inferred (Taseko Mines Limited, 2020). Back-arc basin and mid-oceanic ridge VMS (Besshi and Cyprus) types are less common although there are important examples of both (e.g., back-arc Windy Craggy, Granduc, and Goldstream; mid-ocean ridge in the Anyox camp). Chu Chua is an exploration-stage mid-oceanic ridge deposit in the Fennel Formation (Mississippian to Permian). An updated resource estimate has an Inferred 2.29 Mt resource grading 2.11% Cu, 0.30% Zn, 9.99 g/t Ag, and 0.50 g/t Au. Cobalt values of 310-475 ppm were noted historically in the ore zone (Raffle et al., 2021).

In the last decade, the stratigraphy, volcanology, sedimentology, structural geology, geochronology, and isotopic evolution of VMS-bearing rocks and allied intrusions in northwestern British Columbia have been intensively studied (e.g., Nelson and Kyba, 2014; Cutts et al., 2015; van Straaten and Nelson, 2016; Nelson, 2017; Nelson et al., 2013b, 2018) and recently synthesized (Nelson and van Straaten, 2020; Colpron and Nelson, 2021; Nelson et al., 2022; van Straaten et al., 2022). Recent mapping in the Kitsault River area (Hunter and van Straaten, 2020; Hunter et al., 2022; Miller et al., 2023) indicates that precious metals-enriched VMS mineralization is slightly older than in what is traditionally considered the bounds of the Eskay rift to the west. Mihalynuk et al. (2019) presented U-Pb zircon data consistent with VMS mineralization at the Granduc and Rock and Roll deposits being Late Triassic. In northern British Columbia, Mihalynuk et al. (2024) are examining ophiolitic rocks near Atlin for ultramafic-associated massive sulphide mineralization, and in southeastern British Columbia, the Survey is currently examining ultramafic-associated Ni- and Co-enriched VMS mineralization in the Lardeau Group.

5.3. Deep-water basin and platformal base-metal systems

Sedimentary exhalative (SEDEX) and Mississippi Valley-type (MVT) deposits are the most significant hosts of base-

metals genetically related to the deposition and diagenesis of sedimentary rocks in British Columbia. Potential exists for other types in which sedimentary processes play a predominant role. These two deposit types (SEDEX and MVT) are included in the broad class referred to as ‘sediment-hosted (D)’ by Lefebvre and Jones (2022).

SEDEX deposits, such as the historic Pb-Zn-Ag Sullivan mine (Fig. 10), typically form in deep-water, off-shelf settings coeval with background sedimentation of fine-grained argillaceous material (Fig. 11). In ‘vent-proximal’ deposits, sulphide minerals grow near hydrothermal seafloor vents surrounded by fine-grained sediments. ‘Vent-distal’ deposits lack an apparent relationship to hydrothermal vents entirely and display a stratiform geometry with alternating sulphide-rich and fine-grained interlayers (e.g., Goodfellow and Lydon, 2007; Sangster, 2018). Both represent the syndepositional accumulation of sulphide minerals derived from waters that have circulated through underlying basement rocks and the sedimentary pile and ascended to the sediment-water interface or close to it. The primary metals in SEDEX deposits are Pb and Zn (\pm Ag, Ge, In); some have a spatial association with stratiform barite deposits. Historical records indicate the Sullivan mine contained Sn, Cu, Au, Fe, Sb, Cd, Bi, In, and W.

In contrast to the typical deep-water setting of SEDEX deposits, Mississippi Valley-type (MVT) deposits are hosted by relatively shallow-water platformal carbonate successions (Fig. 11) in which both penecontemporaneous dolomitization of original calcium carbonate sediment and karst processes create void spaces for the precipitation of base-metal sulphides from low-temperature hydrothermal fluids to form stratabound epigenetic deposits (e.g., Sangster, 1990; Paradis et al., 2007). Lead and Zn are the primary metals, but MVT-like deposits have potential to contain Mg, Ga, Ge, In, REE, and F (e.g., Mt. Brussilof mine where Mg is now being produced, Fig. 10). Barite is a potential primary commodity, and at least one REE (F, Ba)-bearing deposit (Rock Canyon Creek) has similarities in tectonic and stratigraphic setting to Mississippi Valley-type Zn-Pb deposits in the same district (Simandl et al., 2019).

Other deep-water basin and platform-hosted mineralization types in the Cordillera include ‘hyper-enriched black shales’ and ‘sediment-hosted Cu’ (‘red-bed’, or Kupferschiefer-type). Hyper-enriched black shales deposited off-shelf of the Laurentian margin (Kechika trough) in the Middle Devonian (Gadd et al., 2020, 2022b), can contain concentrations of Zn, Ni, Cu, Mo, Se, U, V, Cr, Co, Ag, Au, Re, PGE and REE, and Gadd et al. (2022b) described an example below younger SEDEX mineralization at the Akie deposit. Redbed copper deposits in marginal marine evaporites and related rocks of the Coates Lake Group (Neoproterozoic, Mackenzie Mountains, NT) display both syngenetic and epigenetic styles (e.g., Ootes et al., 2013; Brown et al., 2014) and there may be potential for this type of mineralization in Neoproterozoic units in northern British Columbia. Sedimentary or volcanic-hosted Cu mineralization also occurs in the Takla and Hazelton groups (Late Triassic to Early Jurassic) in eastern Stikine terrane (e.g., Sustut copper

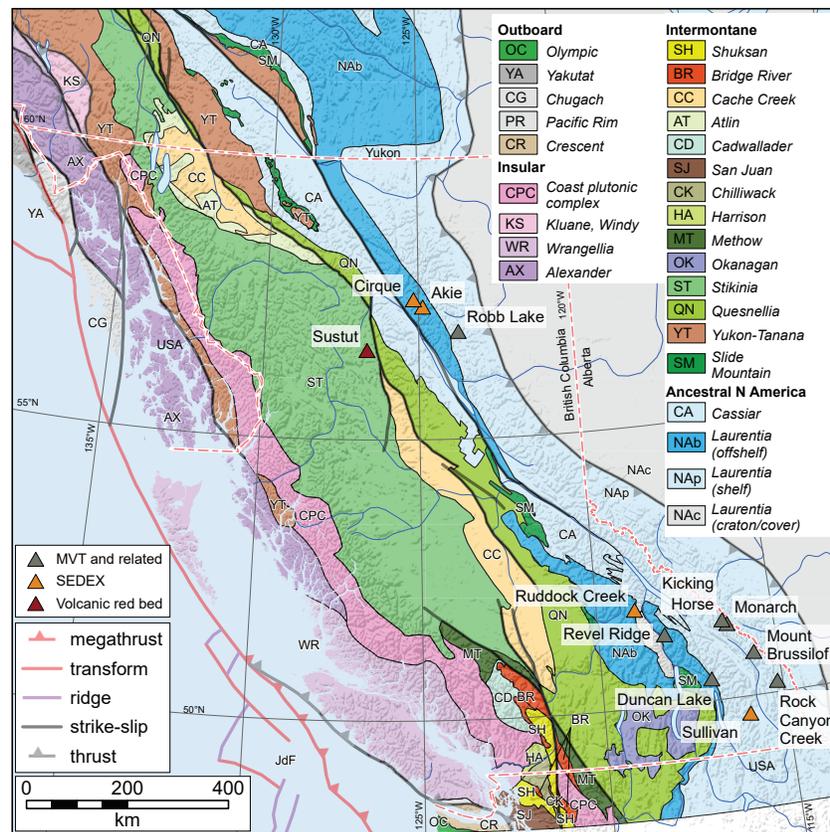


Fig. 10. Selected sedimentary exhalative (SEDEX) and Mississippi Valley Type (MVT) deposits in British Columbia. Terranes after Colpron (2020).

deposit; Church, 1975; Legun, 2001, Fig. 10), although the timing of mineralization remains unknown.

Consistent with the global distribution of such base metal deposits (Hoggard et al., 2020; Huston et al., 2023), SEDEX and MVT deposits in British Columbia formed in extensional tectonic settings, particularly related to the development of cratonic margins (e.g., Emsbo, 2009; Fig. 11). The famous Sullivan deposit (Figs. 10, 12) formed in the deeper parts of the Belt-Purcell basin in an intracratonic sag generated by stretching of the Laurentian continental nucleus about 1.45 billion years ago (e.g., Lydon et al., 2000; Lydon, 2007). Early Paleozoic SEDEX and MVT deposits formed contemporaneously on the western flank of Ancestral North America during the breakup of the supercontinent Rodinia, suggesting a broad genetic relationship with regional platform to off-shelf fluid flow (Fig. 2; e.g., Nelson et al., 2002, 2013a; Ootes et al., 2013).

Lead isotope studies suggest crustal sources of mineralization in MVT and SEDEX deposits (Godwin and Sinclair, 1982; Nelson et al., 2002; Leach et al., 2005; Ootes et al., 2013). Siliciclastic debris derived from continental basement and carbonate deposits are potential sources (Fig. 2b; Goodfellow and Lydon, 2007; Paradis et al., 2007; Emsbo et al., 2016; Leach et al., 2010). Leach et al. (2005) suggested that mineralization is related to the circulation of large volumes of saline brines, concentrated by the evaporation of seawater, or in the case of MVT, possibly evaporite dissolution (Fig. 11). SEDEX fluids

range from low to high temperature, 70-300°C, and salinities of 10-30 wt.% total dissolved solids, like oilfield brines (Emsbo, 2016 and references therein), whereas MVT are somewhat lower temperature, 75-200°C and up to 30 wt.% equivalent NaCl+CaCl (e.g., Paradis et al., 2007; Kontak et al., 2022). The mechanisms of heating and circulation remain conjectural and may reflect high regional geothermal gradients (with possible magmatic underplating), or deep circulation of brines (Fig. 11b). Proposed mechanisms driving fluid flow include sediment compaction and discharge, heat-driven buoyancy convection, topography-driven flow, and density-driven flow of evaporatively concentrated brines (Emsbo et al., 2016; Wilkinson, 2014; Sangster, 2020).

Syn depositional faults are the foci of mineralizing fluids in SEDEX models (Figs. 11 b, c). In the case of MVT, faults, fractures, breccias and karst features all may supply permissive permeability and porosity (Fig. 11 d). Confluences of physical and chemical conditions that focus and alter mineralizing fluids include changing lithology, changing pressure-temperature, and fluid mixing. In the Cordillera, long-lived basement structures transverse to the structural grain may have exerted controls (Lund, 2008; McMechan, 2012; Hayward and Paradis, 2021). Precipitation of sulphides requires reduced sulphur. A trap involves a change from limestone to dolomite, a permeable organic rich near-seafloor layer, exhalation into euxinic seafloor conditions, or other mixing of fluids with contrasting properties

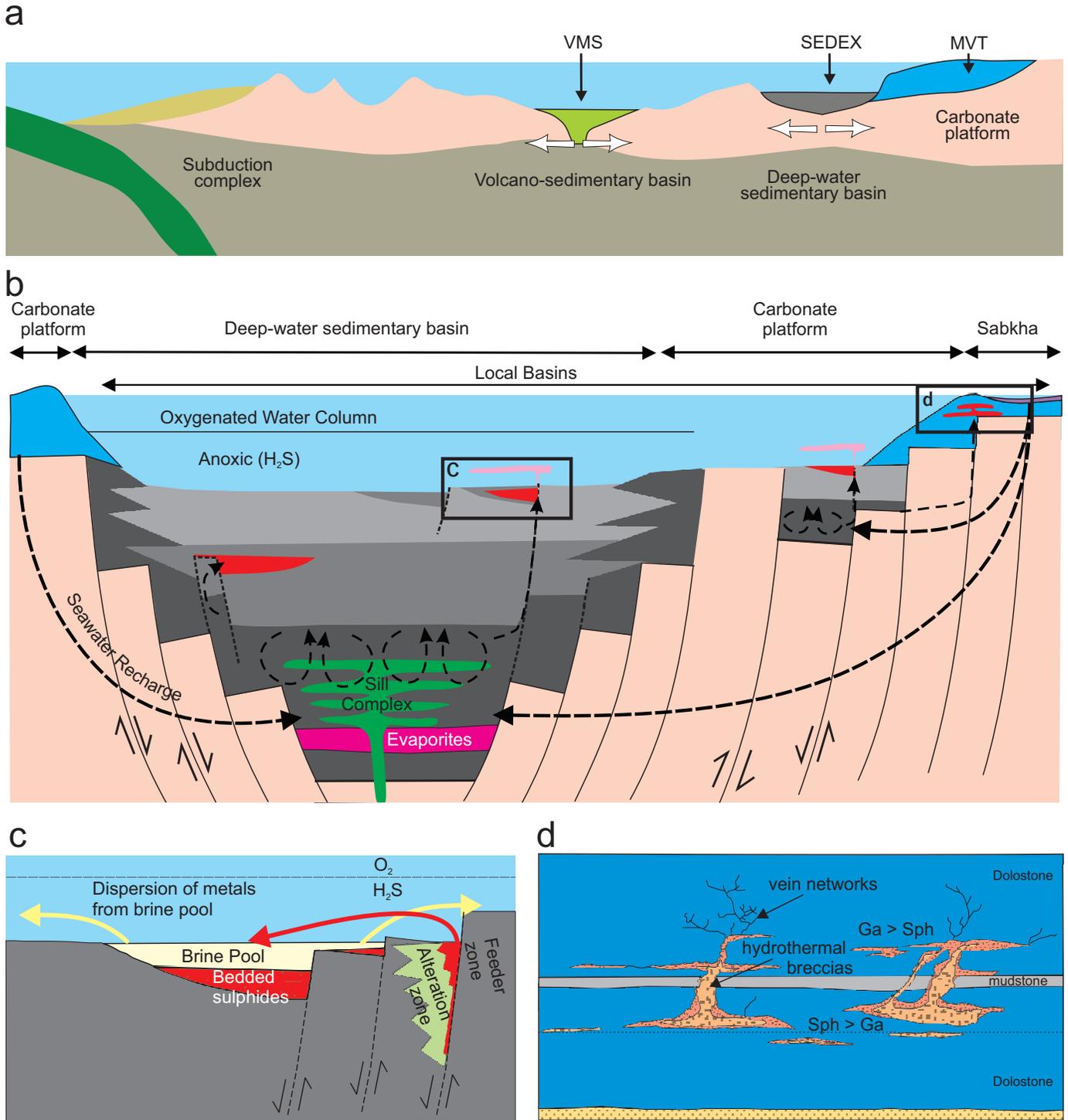


Fig. 11. a Tectonic model showing extensional environments where volcanogenic massive sulphide (VMS), sedimentary exhalative (SEDEX), and Mississippi Valley-type deposits occur. Simplified from Nelson et al. (2002). **b** Schematic diagram showing the relationship between a deep-water sedimentary basin and carbonate platform. Black arrows depict fluid flow through basement and sedimentary basins. Locations of mineralization are red. Black box outlines are for SEDEX and MVT mineralization depicted in c) and d). Simplified from Goodfellow and Lydon (2007). **c** Schematic diagram of vent-distal SEDEX mineralization related to extensional faults and dispersion of metal-rich hydrothermal fluids at the seafloor. Modified after Goodfellow and Lydon (2007). **d** Schematic depiction of MVT mineralization from Robb Lake. Simplified from Paradis et al. (2007).



Fig. 12. Folded bands of massive sulphides interlayered with fine-grained siliciclastic deposits from the historical Sullivan SEDEX mine, southeastern British Columbia.

(e.g., Goodfellow and Lydon, 2007; Leach et al., 2010; Magnall et al., 2020; Kontak et al., 2022).

British Columbia is home to numerous SEDEX deposits. The Ruddock Creek deposit is in isoclinally folded amphibolite facies metasedimentary rocks (Höy, 2001, 2002) in the hanging wall of a crustal-scale ductile shear (Monashee decollement). Based on sulphide lead isotope ages, mineralization formed between Neoproterozoic deposition (ca. 663 Ma) and ca. 535 ±30 Ma (Theny et al., 2015; Theny, 2016). The resource stands at 6.25 Mt grading 6.50% Zn, 1.33% Pb Measured and Indicated and 6.68 Mt grading 6.33% Zn, 1.20% Pb Inferred, based on a 2013 estimate (Imperial Metals Corporation, 2023) that does not include more recent drill results. SEDEX deposits in offshore rocks of the northern Rocky Mountain Laurentian margin are Late Devonian, hosted by carbonaceous shale of the Gunsteel Formation (Upper Devonian), Earn Group, and include vent-proximal and, more commonly, vent-distal types (Goodfellow, 2007). Cirque, a vent-distal deposit, currently has the largest (historical) resource estimate with 38 Mt of 8% Zn, 2.2% Pb, and 47.2 g/t Ag for the main Cirque, and 15.5 Mt of 6.9% Zn, 1.4% Pb, and 32 g/t Ag for the south Cirque (MacIntyre, 1992). The Akie project includes the Cardiac Creek vent-proximal deposit, which has an Indicated resource of 22.7 Mt of 8.32% Zn, 11.61% Pb, and 14.1 g/t Ag, and an Inferred resource of 7.5 Mt of 7.04% Zn, 1.24% Pb, and 12.0 g/t Ag (JDS Energy & Mining Inc., 2018).

Most MVT and related deposits in British Columbia are in early stages of modern exploration, (e.g., Robb Lake, Duncan Lake) or have been mined out (e.g., Monarch, Kicking Horse). However, the Revel Ridge project is a more advanced project with a zone of carbonate-hosted Ag-Zn-Pb mineralization variously described as metamorphic complex lead-zinc type (like Ruddock Creek) or MVT as favoured in a recent compilation by Stone et al. (2021). The total resource estimate

across all zones, including veins, is 6.7 Mt of 1.93% Pb, 3.68% Zn, 50 g/t Ag, and 3.69 g/t Au Measured and Indicated and 6 Mt of 1.19% Pb, 2.20% Zn, 39 g/t Ag, and 4.70 g/t Au Inferred. Although Late Devonian SEDEX mineralization in the Earn Group prompted exploration at the Silvertip deposit, the primary target is currently considered to be related to an enigmatic Cretaceous intrusion and represent a carbonate replacement manto (Nelson and Bradford, 1993; Cullen, 2010.)

Decades of foundational mapping and deposit studies in British Columbia that followed the pioneering work of Fyles and Eastwood (1962), Fyles (1964), Höy (1983), among others continues today with focus on comparing different carbonate-hosted deposits. Paradis et al. (2022) reviewed carbonate-hosted deposits of the southeastern Canadian Cordillera, including paragenetic and isotopic data and concluded that most formed in high-porosity dolostones at the margins of carbonate platform and that mineralization occurred predominantly in two main episodes: Middle to Late Cambrian and Late Devonian to Middle Carboniferous. Simandl et al. (2020, 2022) compared the REE contents of carbonate minerals in Pb-Zn deposits, finding general evidence of re-equilibration with diagenetic, hydrothermal, or metamorphic fluids. Kontak et al. (2022) compared petrographic, fluid inclusion, and stable isotope data of MVT deposits in British Columbia and Alberta suggesting that mixing of sulphur-poor metalliferous and sulphide bearing metal-poor fluids generally plays a role in mineralization. Paradis and Simandl (2017, 2018) considered genetic links between MVT and SEDEX types and between carbonate hosted barite-Zn and magnesite. Green et al. (2017) and Simandl et al. (2019) noted the similar setting of the Rock Canyon Creek deposit, which includes REE-bearing fluorocarbonates, phosphates, and fluorite (Hoshino et al., 2017), and MVT deposits of southeastern British Columbia.

5.4. Magmatic mafic to ultramafic systems

Magmatic sulphide deposits in mafic-ultramafic intrusions are the main hosts of Ni and platinum-group elements (PGE) globally and in British Columbia (Mudd and Jowitt, 2014; Mudd et al., 2018). These deposits form where sulphide liquid can segregate from a silicate magma, interact with this magma to become enriched in metals, and accumulate in small volumes of mafic-ultramafic rock in accessible portions of the crust (Naldrett, 1999; Barnes et al., 2015; Lawley et al., 2021). In the BCGS deposit profile classification (Lefebvre and Jones, 2022), the general ‘mafic/ultramafic’ (M) category of this mineralizing system includes the ‘flood basalt-associated Ni-Cu’ (M01), ‘gabbroid stocks Ni-Cu’ (M02), ‘Alaskan-type Pt±Os±Rh±Ir’ (M05), and ‘Giant Mascot-type Ni-Cu±Co (M09)’ subcategories. The main metals of economic interest are Ni, Cu, Co, and the PGE (Pt and Pd > Os, Ir, Rh, and Ru; Mudd and Jowitt, 2014; Mudd et al., 2018). However, these deposits can also contain significant concentrations of V, Ti, and Cr, which are hosted primarily by chromitites and Fe-Ti-V oxide ores (Cawthorn et al., 2005; Mondal and Mathez, 2007; Pang et al., 2008) and Sc, which is concentrated

principally in clinopyroxene and amphibole (Wang et al., 2021b). Metalloids (e.g., Bi, As, Te, and Pb) that may be associated with platinum-group minerals (PGM) are rarely present in economic concentrations.

Magmatic Ni-Cu-PGE sulphide deposits can be hosted by layered mafic plutons, such as the Bushveld Complex in South Africa (e.g., Maier et al., 2023) and Duluth Complex in USA (e.g., Thériault et al., 2000), or volumetrically smaller conduit-type plutons, such as the Current (Brzozowski et al., 2023), E&L (Hancock, 1990; Brzozowski and Zaborniak, 2024), and Voisey's Bay (Lightfoot et al., 2012) deposits in Canada. It is generally agreed that most of these deposits formed from parental magmas generated by high degrees of partial melting of mantle plumes beneath craton boundaries (Fig. 13a; Begg et al., 2010), forming Large Igneous Provinces (Ernst and Jowitt, 2013). Subduction zones have not traditionally been considered prospective targets for magmatic sulphide deposits because of the paucity of mafic-ultramafic intrusions containing economic concentrations of Ni (Ripley, 2010). This view is rapidly changing as increasingly more Ni-Cu-PGE deposits are identified at convergent margins (Fig. 13b) around the world such as in Spain (e.g., Aguablanca, Piña et al., 2010) and China (e.g., Huangshandong, Huangshanxi, and Kalatongke, Song and Li, 2009; Mao et al., 2014; Wang et al., 2021a). In British Columbia (Fig. 14), such deposits include Giant Mascot (Manor et al., 2016), Turnagain (Scheel et al., 2005; Jackson-Brown et al., 2014; Nixon et al., 2019), E&L (Brzozowski and Zaborniak, 2024), Tulameen (Spence et al., 2022), and Polaris

(Nixon et al., 1990; Nott et al., 2020; Milidragovic et al., 2021, 2023).

Regardless of tectonic setting, the mechanisms by which magmatic sulphide deposits form are largely the same (Fig. 15). These include: 1) generation of a mafic-ultramafic magma by high degrees of mantle partial melting; 2) segregation of an immiscible sulphide liquid from the magma; 3) migration of this sulphide- and crystal-laden magma upwards through the crust; and 4) enrichment of the sulphide liquid in metals (Naldrett, 2010). A high degree of mantle partial melting is critical to generating these deposits because it allows for complete melting of sulphides in the mantle source, which releases metals to the resulting magma (Arndt et al., 2005; Naldrett, 2010). Despite the importance of generating an immiscible sulphide liquid, this process is challenged because most magmas arriving near the Earth's surface are undersaturated in sulphide; this is particularly true for the oxidized magmas that form at convergent margins (Mavrogenes and O'Neill, 1999; Jugo, 2009). Some additional mechanism is, therefore, required to cause a magma to become saturated in sulphide, the most common of which being addition of external S, although addition of Si, magma mixing, and crystal fractionation can also lead to sulphide saturation (Ripley and Li, 2013). Transport of the crystal- and sulphide-laden magma from the mantle to the upper portion of the crust is driven by buoyancy and dike propagation, with sulphide transport possibly being assisted by flotation on vapor bubbles (Barnes et al., 2015; Yao and Mungall, 2020). Craton boundaries serve as ideal structural

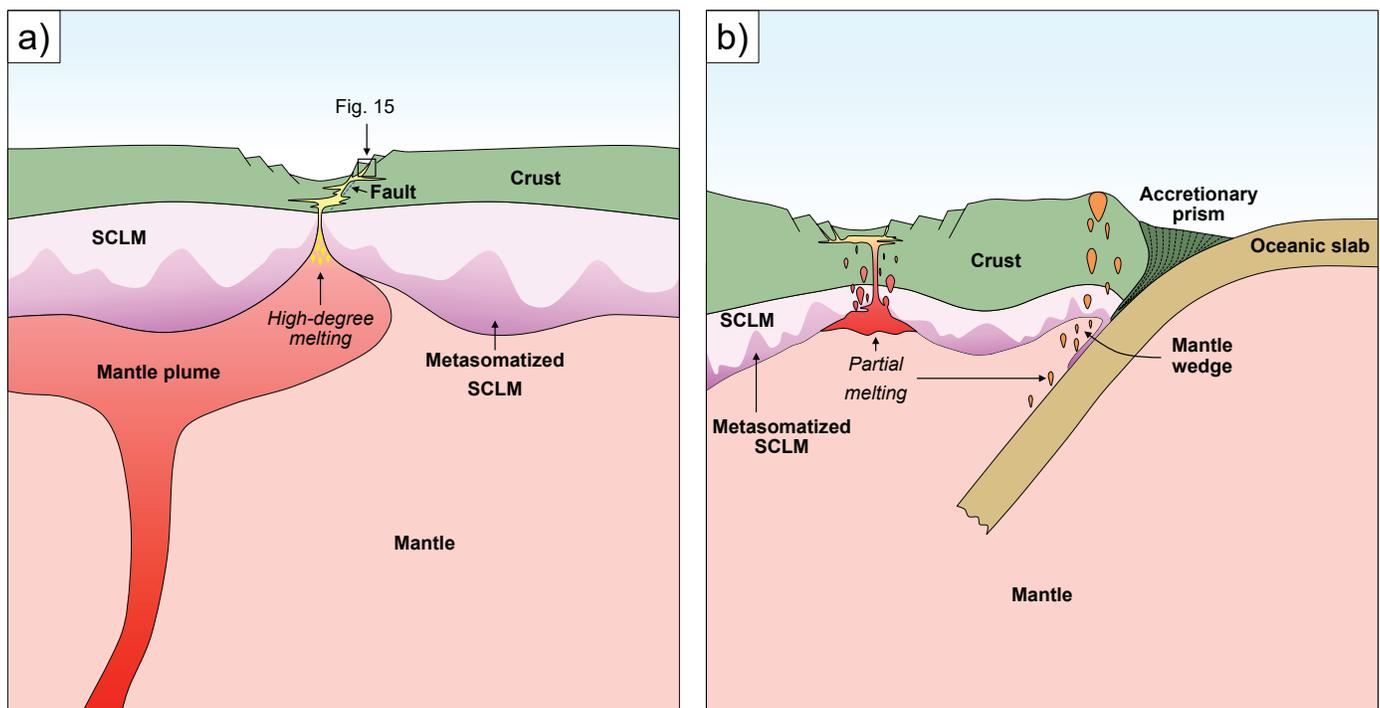


Fig. 13. Schematic diagrams illustrating the generation of magmas and associated mafic-ultramafic intrusions in **a)** an intracontinental setting associated with a mantle plume and **b)** a convergent margin (modified after Jiang et al., 2019). Most mafic-ultramafic plutons in British Columbia formed from arc-related magmas at convergent margins. Some mineralized Alaskan-type intrusions appear to have been emplaced coeval with (e.g., Polaris) or just preceding (e.g., Turnagain) the accretion of major arc terranes in the northern Cordillera (Nixon et al., 2019, 2020b).

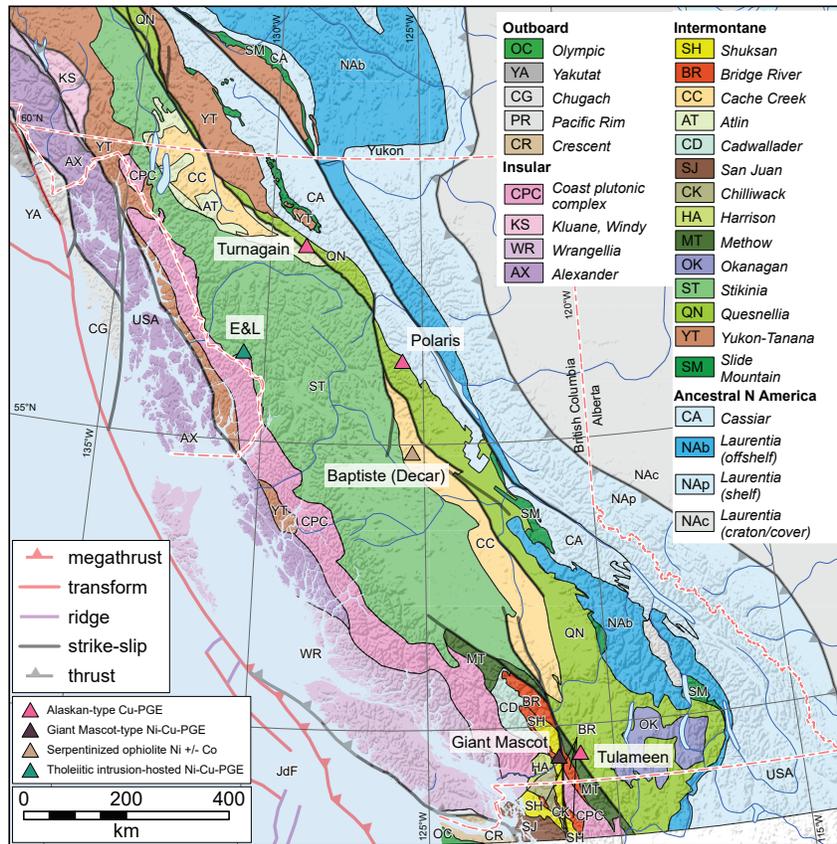


Fig. 14. Selected mafic-ultramafic Ni-Cu-PGE deposits in British Columbia. Modified after Nixon et al. (2020b). Terranes after Colpron (2020).

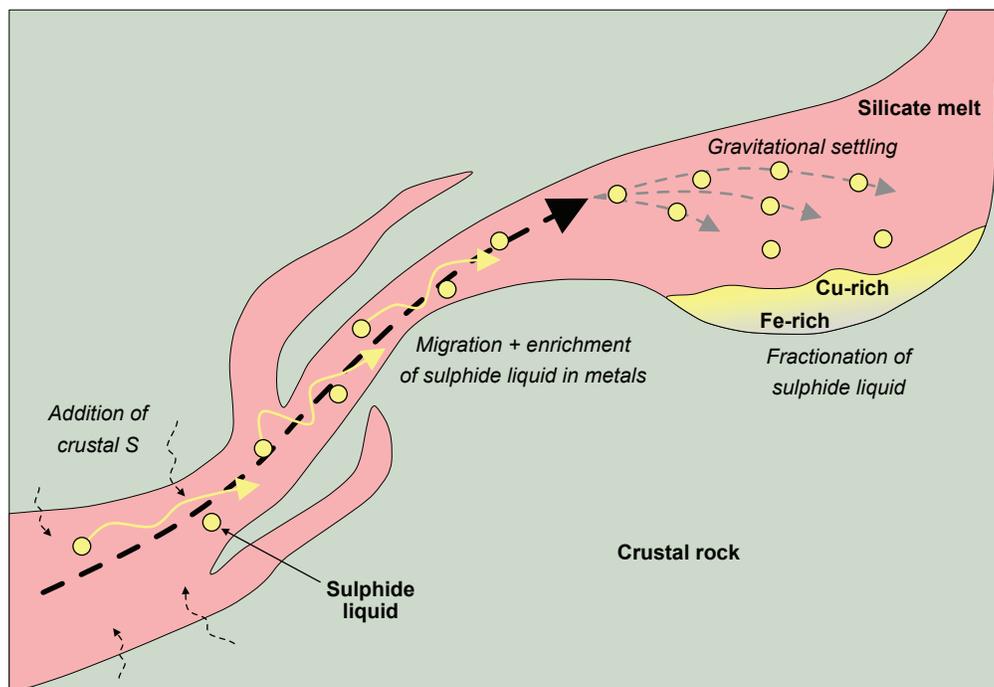


Fig. 15. Schematic diagram illustrating the range of intrusion-scale processes that operate to form base- and precious-metal-rich magmatic sulphide deposits. These processes include the: addition of externally derived S; generation of an immiscible sulphide liquid; enrichment of the sulphide liquid in metals via interaction with silicate melt; gravitational settling of the dense sulphide liquid; fractionation of the sulphide liquid and formation of Fe-rich monosulphide solid solution and Cu-rich intermediate solid solution; and exsolution of pyrrhotite-pentlandite from monosulphide solid solution and chalcopyrite from intermediate solid solution.

corridors for magma transport because Moho-penetrating faults can be reactivated, allowing magmatism to be concentrated (Barnes et al., 2015). Smaller-scale migration and emplacement occurs where these deep faults interact with local crustal anisotropies, such as faults, fractures, and foliation (Barnes et al., 2015). During magma transport and emplacement, the immiscible sulphide liquid becomes progressively enriched in metals by selectively concentrating dispersed metals in the magma via sulphide liquid-silicate melt interaction (Mungall et al., 2020). This metal enrichment process, which is quantified as 'R factor' (Campbell and Naldrett, 1979), operates most effectively in dynamic magma systems where small volumes of sulphide liquid can interact with large volumes of silicate melt (e.g., conduit-type intrusions, Barnes and Lightfoot, 2005). Finally, the metal-rich sulphide liquid needs to be concentrated in traps via mechanical processes related to silicate melt-sulphide liquid density differences and changes in magma flow regime (Barnes et al., 2015). These traps largely occur where the morphology of conduits change, causing a change in magma dynamics and, hence, sulphide carrying capacity (e.g., embayments, changes in conduit orientation; Evans-Lamswood et al., 2000; Barnes et al., 2015).

Nickel-Cu-PGE sulphide deposits in British Columbia (Fig. 14) are almost exclusively hosted by Alaskan-type and other mafic-ultramafic intrusions in Quesnel and Stikine terranes. The intrusion-hosted deposits are mineralogically and metallogenically distinct; some are endowed in PGE, but have limited sulphide (e.g., Tulameen, Polaris), whereas others are endowed in base metals and are sulphide rich (e.g., Giant Mascot, Turnagain, E&L). The Giant Mascot deposit, which is hosted by dunite, peridotite, and olivine-bearing pyroxenite that intruded the Settler schist and Spuzzum pluton (Coast Plutonic complex), is the only previously mined Ni-Cu-PGE deposit in British Columbia. It contains disseminated, net-textured, and (semi-) massive orebodies comprising chalcopyrite, pyrrhotite, and pentlandite (Nixon, 2003; Manor et al., 2016). At Turnagain, Ni-Cu-PGE mineralization in the form of disseminated to semi-massive pyrrhotite, pentlandite, and lesser chalcopyrite occurs predominantly in the dunite-wehrlite core of an otherwise typically zoned Alaskan-type pluton that intruded greenschist-facies volcano-sedimentary strata (Nixon, 1998; Scheel et al., 2005; Jackson-Brown et al., 2014; Nixon et al., 2020b). The Polaris Alaskan-type intrusion was emplaced into metasedimentary and metavolcanic rocks of the Lay Range assemblage in Quesnel terrane. It contains Ir-rich mineralization in chromite-bearing dunite and Cu-Pt-Pd-Au-rich magmatic sulphide in clinopyroxenite (Nixon et al., 1997; Nott et al., 2020; Milidragovic et al., 2021, 2023). The Tulameen intrusion, in the southern part of Quesnel terrane, is a zoned, sill-like Alaskan-type body emplaced into metavolcanic and metasedimentary rocks of the Nicola Group. It contains sulphide-poor, PGE-rich mineralization in chominites in the dunite core and sulphide-rich, Cu-PGE mineralization in clinopyroxenites in a peripheral zone. At the E&L deposit, which is hosted by a tholeiitic gabbro stock that cuts Lower

Jurassic Hazelton Group rocks in Stikine terrane, sulphide-rich Ni-Cu-PGE mineralization consists of chalcopyrite, pyrrhotite, and pentlandite mainly in varitextured gabbro and wehrlite (Vandenburg, 2020; Brzozowski and Zaborniak, 2024). Although not as common, Ni mineralization also occurs in serpentinized ophiolites. These deposits are genetically distinct from magmatic sulphide deposits and form, in part, by the release of Ni from olivine because of hydrothermal alteration. An example of such a deposit in British Columbia is Baptiste, in the Mount Sidney Williams ultramafic-ophiolite complex of Cache Creek terrane. Mineralization is in the peridotite as disseminated awaruite (Ni-Fe alloy) that resulted from serpentinization of Ni-rich olivine (Britten, 2017).

In the last several decades, British Columbia Geological Survey programs have undertaken research characterizing the petrogenesis of magmatic sulphide deposits and their host mafic-ultramafic plutons, particularly those in the accretionary terranes (e.g., Hancock, 1990; Nixon et al., 1990, 1997; Nixon, 1998, 2003). Recent work has built upon these foundational studies to continue expanding our understanding of these economically significant deposits. Manor et al. (2014) and Jackson-Brown et al. (2014) provided the first published details of the mineralogy of sulphides and platinum-group minerals in the Giant Mascot and Turnagain sulphide-rich deposits, respectively. Milidragovic et al. (2017) developed a magma mixing model to explain unusually Fe-rich rocks of the Mount Hickman intrusive system, contributing to our understanding of barren versus fertile Alaskan-type plutons. Nott et al. (2020) refined the lithological units of the Polaris pluton that were originally defined by Nixon et al. (1997), identified lithological characteristics indicating remobilization of ultramafic cumulates triggered by magma recharge, and described the spatial variability of sulphide-rich and sulphide-poor PGE mineralization. Milidragovic et al. (2023) presented sulphur isotopic data indicating that seawater sulphate was added to the sub-arc source of the Polaris magmas. Spence et al. (2022) mapped the textural relationships between ultramafic cumulates of the Tulameen pluton, and identified zones of intermingled ultramafic cumulates that were interpreted as evidence for magma recharge and remobilization of crystal mushes. Steinhorsdottir et al. (2020) described the alteration and protoliths of a dismembered ophiolite containing the Baptiste deposit and highlighted the potential importance of the degree of serpentinization to the distribution, abundance, and grain size of brucite and awaruite.

As part of the current critical minerals program at the Survey, ongoing research to further our understanding of the spectrum of magmatic sulphide deposits in the province was initiated at the E&L deposit (Brzozowski and Zaborniak, 2024).

5.5. Carbonatite and related systems

Carbonatites are rare igneous rocks that contain abundant primary carbonate minerals, at least 30% (Mitchell, 2005) or 50% (Le Maitre, 2002). As the exclusive source of critical metals such as Nb and REE, these rare rocks have become

important exploration targets. Most carbonatites are spatially and temporally associated with much larger volumes of silicate rocks such as ultramafic, melilitic, ijolite-series, and syenitic rocks, suggesting genetic relationships between the carbonate and the silica-undersaturated and alkaline silicate magmas (Woolley, 2003; Mitchell, 2005; Woolley and Kjarsgaard, 2008). The deposit profile scheme of Lefebure and Jones (2022) refers to carbonatite deposits as ‘carbonatite-associated deposits: magmatic, replacement, and residual (N01); and to related rock deposits as “nepheline syenites” (R13)’. Carbonatite- or related rock-hosted deposits also produce fluorapatite, phosphate, Fe, Al, Ti, Zr, V, Cu, Ni, Au, PGE, Ta, Mo, Ba, Sr, Th, U, lime, olivine, phlogopite, and vermiculite as the main commodities or bi/co-products (Mariano, 1989). Mitchell and Gittins (2022) distinguished the high-temperature magmatic carbonatites from the low-temperature, deuteric, residual ‘carbothermalites’ resulting from fluids enriched with CO₂ and/or carbonate anions. Both carbonatites and carbothermalites are important sources of critical metals such as Nb and REE, but carbothermalites can derive from different magmas found in a wider range of tectonic settings than carbonatites. Thus, identifying the hosts is important for critical mineral exploration. Major global examples of carbonatite-hosted deposits include REE producers such as Bayan Obo in China (Kynicky et al., 2012) and Mountain Pass in the USA (Castor, 2008) and Nb producers such as Araxá in Brazil (Biondi, 2005) and St. Honoré in Canada (Néron et al., 2018). Elsewhere, Mo production at Huanglongpu in central China is an example of an economic carbothermalite-hosted Nb-U-REE-Mo deposit within an orogenic belt (Xu et al., 2010; Song et al., 2016). Pegmatite-hosted rare-metal deposits include Nb-Y-F (e.g., Strange Lake, Québec) related to peralkaline granites or syenites and Li-Cs-Ta (e.g., Greenbushes, Australia) related to peraluminous S-type granites (e.g., Černý and Ercit, 2005; Goodenough et al., 2019).

Globally, carbonatites are typically restricted to intracratonic settings as part of crustal-scale doming and extensional systems (e.g., Bell, 1989). However, the origin and ultimate source of carbonatite-hosted critical metals on the one hand and peralkaline granite and syenite-hosted Nb, Ta, and REE on the other remains controversial. Both the lower mantle and recycled materials have been suggested as sources for carbonatite magmas (Rukhlov et al., 2015, 2018, 2019; Çimen et al., 2019), whereas peralkaline granitic and syenitic hosts might have formed by partial melting of a metasomatized lower crust (Martin, 2012). Carbonatite magmas can be the products of immiscible separation or fractional crystallization of parental carbonated silicate magmas, or the products of low-degree partial melting of a carbonate-bearing mantle (Bell, 1989; Bell and Rukhlov, 2004; Berkesi et al., 2023; Gittins and Mitchell, 2023). Ubiquitous fluoride and oxyfluoride complexes in the Nb-Y-F pegmatites suggest an important role of F for Nb transport and enrichment in these systems (Mitchell, 2015). The magmatic evolution of rare-metal pegmatites is characterized by progressive Ta enrichment and roughly

concentric zoning due mainly to in-situ differentiation (Černý et al., 1986). These systems derive from volatile-rich, highly evolved, felsic magmas (Černý and Ercit, 2005). Crustal-scale faults control pathways of both mantle- and crust-derived melts and fluids that concentrate, transport and precipitate Nb, Ta, and REE. Based on experimental evidence, Anenburg et al. (2020) concluded that complexing with alkalis, in addition to halogens and carbonate anions, are required for transport and trapping of economic-grade, carbonatite-hosted REE deposits (Trofanenko et al., 2016).

In the Canadian Cordillera, carbonatite and related igneous bodies (Fig. 16) were emplaced episodically at ca. 810-700 Ma (Mount Copeland, Perry River, Ren), 500-400 Ma (Blackfoot Creek, Bush River, Felix, HP, Kechika River, Little Chicago, Mons Creek, Swanson Peak), and 360-320 Ma (Aley, Howard Creek, Ice River, Lonnie, Mount Grace, Mud Lake, Ospika, Paradise Lake, Serpentine Creek, Three Valley Gap, Upper Fir, Trident Mountain, Vergil, Verity, Wicheeda); the Cross kimberlite is 245 Ma. Collectively, these rocks form part of the British Columbia alkaline province, which defines a long (at least 1000 km), narrow (ca. 200 km) orogen-parallel belt along the western flank of Ancestral North America (Scammell and Brown, 1990; Rukhlov and Bell, 2010; Millonig et al., 2012; Millonig and Groat, 2013; Chakhmouradian et al., 2015; Rukhlov et al., 2018). Similar to the intracratonic tectonic setting of carbonatites globally, the Neoproterozoic and Cambrian carbonatites were injected during the protracted breakup of the supercontinent Rodinia and subsequent passive margin development on the western flank of Laurentia (Figs. 17 a, b; Bond and Kominz, 1984; Ross, 1991; Colpron et al., 2002; Li et al., 2008). Both the Neoproterozoic and Cambrian pulses of carbonatite magmatism were accompanied by the emplacement of the large igneous provinces (LIP) such as Gunbarrel, Franklin-Thule, Gataga-Edwardsburg, Hamill-Gog, and Wichita (Ernst and Bleeker, 2010). In contrast, the more numerous late Paleozoic carbonatites, which host Nb-Ta deposits (e.g., Upper Fir in the Blue River area and Aley) and REE deposits (e.g., Wicheeda) are unusual relative to typical global occurrences (Bell, 1989) because they were emplaced near the continental margin while subduction was taking place to the west rather than in the cratonic interior during continental breakup (Fig. 17 c; Nelson et al., 2013a).

Hosted by the parautochthonous rocks of the Omineca and Foreland belts, carbonatites and related ultramafic, silica-undersaturated and alkaline silicate rocks in British Columbia range from intrusive complexes with a paucity of carbonatites (e.g., Trident Mountain, Mount Copeland) to carbonatite complexes with a paucity of silicate rocks (e.g., Aley, Blue River, Frenchman Cap). Both the carbonatites and host rocks experienced multiple episodes of deformation and metamorphism during Mesozoic and Cenozoic accretionary tectonics while outboard terranes welded to each other and to Laurentia (Scammell, 1987, 1993; Scammell and Brown, 1990; Pell, 1994; Millonig et al., 2013). Intrusive complexes made up of mainly silica-undersaturated and alkaline silicate rocks, such

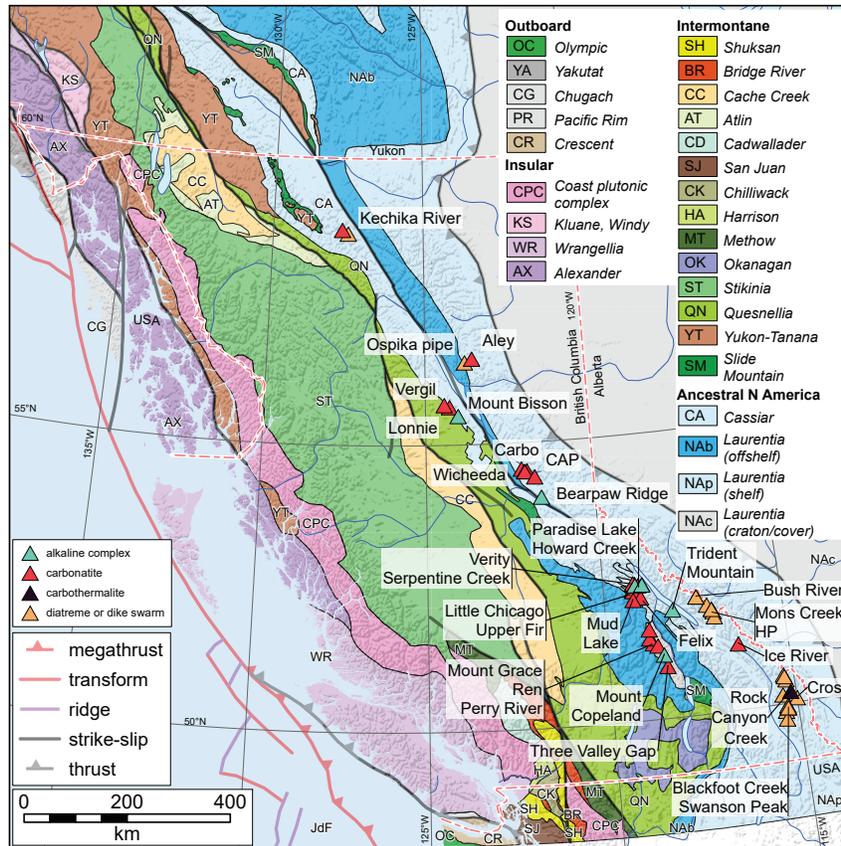


Fig. 16. Carbonatite and related rock occurrences along the British Columbia alkaline province (after Parrish and Scammell, 1988; Pell, 1994; Rukhlov and Bell, 2010; Millonig and Groat, 2013; Rukhlov et al., 2018). Terranes after Colpron (2020).

as the Ice River complex, form small (up to 29 km² at surface), compositionally zoned bodies that are circular to elongate to amoeboid in plan view (Dawson, 1886; Currie, 1975; Peterson and Currie, 1994). Associated REE-Sr-rich carbothermalite dikes, made up of Mn-calcite, barytocalcite, and zeolite with minor strontianite, Nb-ilmenite, and REE-F-carbonates, and ultramafic lamprophyres are common (Mumford, 2009; Brown, 2013). Carbonatites lacking associated contemporaneous silicate rocks typically form regional swarms of individual occurrences across areas of 1000 km² (e.g., Blue River; Pell, 1994; Mitchell et al., 2017; Rukhlov et al., 2018; Çimen et al., 2019). In the Blue River area (Fig. 16), at least 18 carbonatite and two alkaline, silica-undersaturated-rock bodies are exposed, including at the Upper Fir deposit, one of the largest and best studied Nb-Ta occurrences in the Canadian Cordillera (Chudy, 2013; Kulla and Hardy, 2015; Rukhlov et al., 2018). The carbonatites contain 5-10 vol.% amphiboles, 10-15 vol.% fluorapatite, and variable amounts of Ni-rich pyrrhotite, Nb-Zr-REE-Ti oxide phases, zircon, Fe²⁺-Na-rich phlogopite, Ti-rich magnetite, olivine, Fe³⁺-rich ilmenite, and monazite (Fig. 18). Coarse molybdenite (up to 1.7 cm long) occurs sporadically in both carbonatites and metasomatic glimmerites (carbonate-amphibole-phlogopite rocks) and fenites (calcite-clinopyroxene-amphibole rocks; Rukhlov et al., 2018) that mantle carbonatite sills. Molybdenite has been

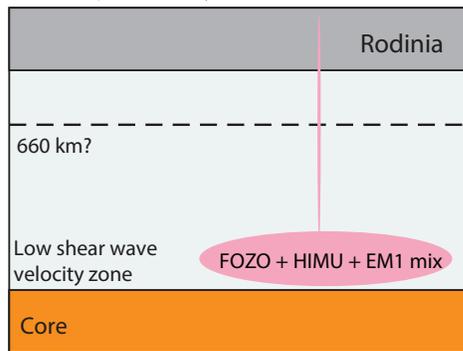
observed in other carbonatite and related-rock occurrences in British Columbia, including Perry River, Mount Grace, Wicheeda, and the Mount Copeland past producer (Currie, 1976; White, 1982; Höy, 1988; Trofanenko et al., 2016).

The Upper Fir carbonatite contains an NI 43-101-compliant resource of 48.4 Mt (Indicated) grading 1610 ppm Nb₂O₅ and 197 ppm Ta₂O₅ plus 5.4 Mt (Inferred) averaging 1760 ppm Nb₂O₅ and 191 ppm Ta₂O₅ (Kulla and Hardy, 2015). The main ore minerals include the Ta±U-rich pyrochlore supergroup and ferrocolumbite, with minor fersmite and nyoboaeschnite (Chudy, 2013; Rukhlov et al., 2018). Ferrocolumbite is the main Nb host in the ferriwinchite (transitional to actinolite)-dolomite carbonatite. In contrast, the ferrikatophorite (transitional to richterite and magnesio-arfvedsonite)-dolomite carbonatite contains predominantly U-Ta±Ti-rich pyrochlore.

Peralkaline granite- or syenite-related Nb-Y-F occurrences such as Mount Bisson and Coryell syenite contain Nb-Ta-Ti-REE minerals. In contrast, peraluminous S-type granite-related Li-Cs-Ta occurrences such as pegmatites in the Shuswap metamorphic complex in the Revelstoke area contain Sn-W-Ti-Ta minerals such as cassiterite, Nb-rutile, qitianlingite, bismutotantalite, hübnerite, and columbite-tantalite group (Dixon et al., 2014). Elsewhere, Li-Cs-Ta deposits are important sources of Li (e.g., Jiajika, China; Greenbushes, Australia; Tanco, Canada; e.g., Goodenough et al., 2019).

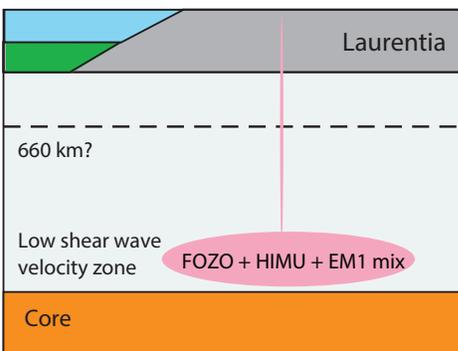
a) ca. 810-700 Ma, Rodinia breakup

Mount Copeland, Perry River, Ren carbonatites



b) ca. 500 Ma, passive margin

Felix, Kechika River, Little Chicago carbonatites



c) ca. 360 to 320 Ma, opening Slide Mountain ocean

Most British Columbia carbonatites

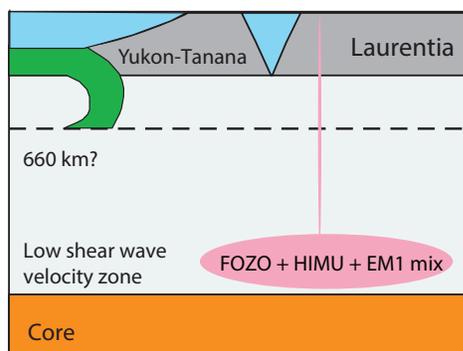


Fig. 17. Pulses of carbonatite magmatism in the Canadian Cordillera and origin of carbonatite-hosted critical metals (after Rukhlov et al., 2019). Parental magmas of Cordilleran carbonatites and related rocks were derived from an extensive, long-lived, deep-level equatorial mantle reservoir (low shear wave velocity zone) at the core-mantle boundary that was tapped episodically since the Neoproterozoic. **a)** ca. 810 to 700 Ma; protracted breakup of the supercontinent Rodinia. **b)** ca. 500 Ma; passive margin development on the western flank of Laurentia. **c)** ca. 360 to 320 Ma; subduction along the western flank of Laurentia and opening of the Slide Mountain ocean as a back-arc basin sourced by MORB magmas. Deep mantle components as follows: FOZO (FOcus ZOne); HIMU (high- $^{238}\text{U}/^{204}\text{Pb}$ or μ); EM1 (enriched mantle 1).

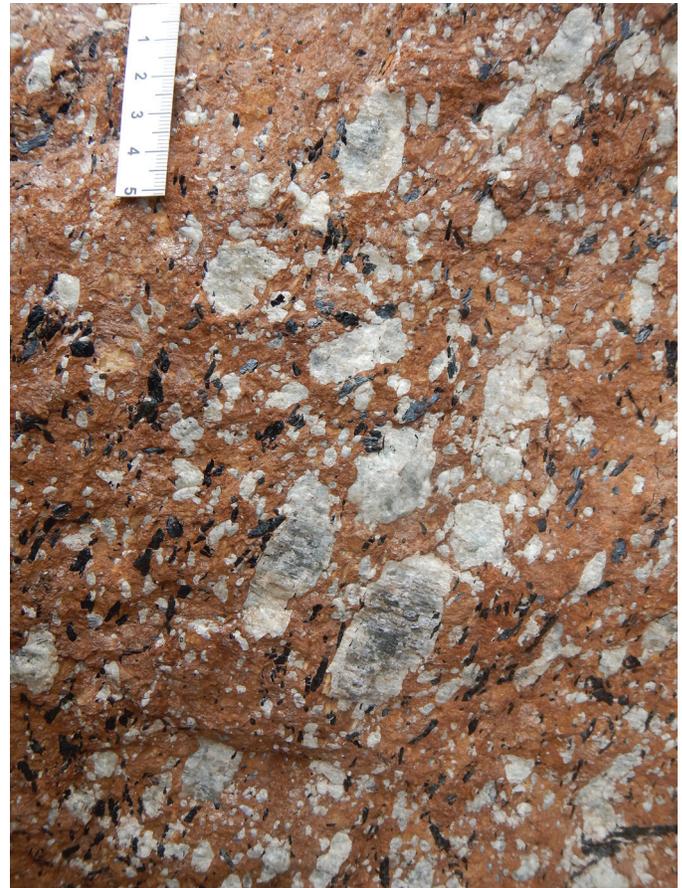


Fig. 18. Dolomite carbonatite with aligned light-toned fluorapatite megacrysts and dark-toned ferriakaphorite prisms set in a recrystallized ferroan dolomite matrix that readily oxidizes brown-red; Upper Fir deposit.

Rukhlov et al. (2018, 2019) examined the petrogenesis of the Blue River carbonatites and other examples from British Columbia using petrographic, whole-rock geochemistry, mineral chemistry, and both stable (C, O, and S) and radiogenic (Sr, Pb, and Nd) isotopic data. Isotopic systematics provide key constraints on magmatic evolution and source of the carbonatite-hosted critical metals. Despite metamorphism and deformation, most carbonatites in British Columbia, except the late Paleozoic Nb-Ta and REE carbothermal rocks, retain primary mantle carbon and oxygen isotopic signatures (Rukhlov et al., 2018, 2019; Çimen et al., 2019). The oxygen isotope equilibrium temperatures for dolomite, magnetite, ilmenite, zircon, and amphiboles coexisting with calcite in Blue River carbonatites yield values between 689-1079°C, which are much higher than the regional metamorphic temperatures (up to ~700°C) and hence reflect crystallization temperatures of relatively hot, oxidized (ΔQFM or quartz-fayalite-magnetite buffer = -0.5 to +5) magmas (Rukhlov et al., 2018). Furthermore, the Sr-Pb-Nd isotopic data indicate a heterogeneous, sub-lithospheric source of the British Columbia carbonatites involving mixing of isotopically distinct mantle end members such as FOZO (FOcus ZOne), HIMU (high- $^{238}\text{U}/^{204}\text{Pb}$ or μ), and EM1 (enriched

mantle 1; Rukhlov et al., 2019). These mantle end members are found in the sources of ocean-island basalts or ‘hot spots’, young (<200 Ma) carbonatites worldwide, and the mantle plume-related Kola alkaline province (ca. 370 Ma; Rukhlov et al., 2015). The significance of high- $^3\text{He}/^4\text{He}$ FOZO component implies a relatively un-degassed deep-seated source (e.g., van Keken et al., 2002). Notably, the depleted, mid-ocean ridge mantle (DMM) end member, which represents the upper mantle, is excluded from the mixing trends defined by the carbonatite data from British Columbia and elsewhere (Rukhlov et al., 2015, 2018, 2019). Paleogeographic reconstructions place the western margin of Laurentia (Fig. 19; Li et al., 2008; Nelson et al., 2013a) and hence the 810-320 Ma British Columbia alkaline province, above the equatorial large low shear wave velocity province marked by a long-lived and extensive (continent-scale) reservoir at the core-mantle boundary (plume-generation zone; Burke, 2011) consisting of FOZO, HIMU, and EM1 components. Parental magmas of Cordilleran carbonatites and related silica-undersaturated and alkaline silicate rocks were likely derived from this reservoir that was tapped episodically as multiple plumes at different times since the Neoproterozoic (Fig. 17). Emplacement was probably aided by long-lived orogen parallel and orogen transverse lithospheric structures that were reactivated by regional tectonic processes during intracontinental rifting (Neoproterozoic, breakup of Rodinia), rifting of Ancestral North America (early Paleozoic, Cordilleran passive margin), and back-arc extension (late Paleozoic; during opening of Slide Mountain ocean as a back-arc basin west of the continental margin).

Simandl et al. (2017) used automated mineralogical analysis to evaluate carbonatite indicator minerals in stream sediments (Mackay and Simandl, 2015). To refine prospecting criteria for carbonatite-hosted critical metals and identify new potential targets, Rukhlov et al. (2024) are currently evaluating provincial drainage geochemistry collected as part of the Regional Geochemical Survey program.

5.6. Iron skarn, iron oxide-apatite (IOA), and iron oxide-copper-gold (IOCG) systems

British Columbia is not known for Fe skarn, iron oxide-apatite (IOA), and iron oxide-copper-gold (IOCG) deposits. Although these deposits have been explored for in the past, possible examples are not well understood, and the systems are underexplored in the modern context. The systems can host Co and In as well as Cu, REEs, Bi, Ni, and Zn but whether they represent a viable critical mineral opportunity in British Columbia remains largely untested.

Iron skarn, iron oxide-apatite (IOA), and iron oxide-copper-gold (IOCG) deposits typically share close spatial relationships with one another in regional mineral systems (e.g., Skirrow, 2022; Corriveau et al., 2022, and references therein) and commonly show spatial continuity with other deposit types such as copper skarns and alkalic porphyry Au deposits. Although with distinctive textural modes, these iron-rich deposits also share unusual characteristics including:

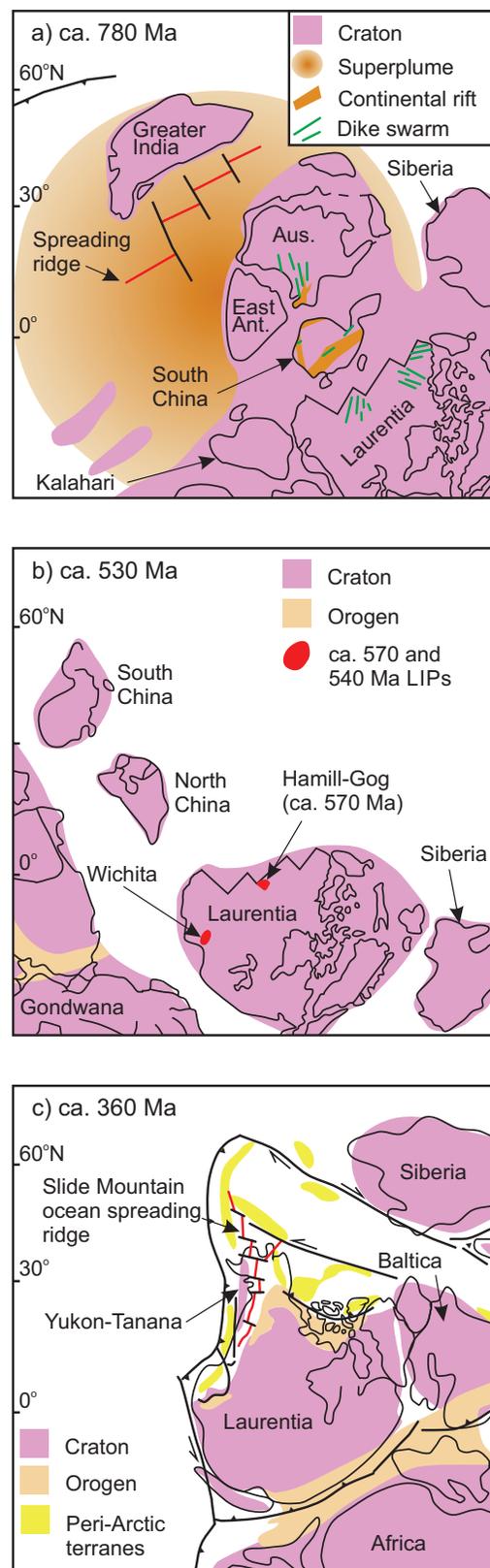


Fig. 19. Paleogeographic reconstructions of Neoproterozoic to Late Paleozoic continents at **a)** ca. 780 Ma; **b)** ca. 530 Ma, and **c)** ca. 360 Ma. The British Columbia alkaline province is in the equatorial and sub-equatorial region. Modified after Li et al. (2008) and Nelson et al. (2013a).

1) massive structurally controlled actinolite-rich magnetite ore bodies that are typically low in Ti and V (Hitzman et al., 1992); 2) regional-scale Na- and Na-Ca alteration and variable deposit-scale Fe-Ca-K alteration; 3) little to no hydrothermal quartz; 4) variable sulphide mineralization consisting mostly of pyrite-chalcopyrite-pyrrhotite (e.g., Sillitoe, 2003; Barton, 2013); and 5) enrichment in a similar spectrum of metals. These shared features make iron skarns, IOA, and IOCG deposits difficult to clearly classify and differentiate from one another and from other deposit types (Sillitoe, 2003; Skirrow, 2022). As a result, the deposit profiles identified by Lefebure and Jones (2022) classify examples of all three deposit types interchangeably in the 'Fe-Skarn (K03)' and 'iron oxide $\text{Cu}\pm\text{Au}\pm\text{P}\pm\text{REE}$ (D07)' groups.

All skarns have abundant garnet-rich calcsilicate alteration and typically develop along contacts between intrusions and carbonate strata (e.g., Meinert et al., 2005). However, iron skarns have distinctive features that set them apart including: 1) mineralization in the form of massive podiform magnetite orebodies (Ray, 2013); 2) abundant sodic-calcic and calcsilicate alteration that mainly replaces Si-rich igneous photoliths rather than carbonate sedimentary rocks (e.g., Golmohammadi et al., 2015; Cui et al., 2022; Mikaeili et al., 2023); and 3) a near complete lack of hydrothermal quartz (Meinert et al., 2005). Along with Fe, iron skarns produce notable quantities of Cu, Co, and Au from pyrrhotite, chalcopyrite, bornite, and arsenopyrite (Meinert et al., 2005) that occurs either as disseminated crystals in massive magnetite or as discrete massive sulphide pods. In addition, In and Ge mineralization have been identified in sphalerite-bearing iron skarns in the American southwest (e.g., the West Desert deposit, USA; Dyer et al., 2014) and elsewhere.

Iron oxide-apatite deposits commonly consist of tabular dike-like or, more rarely, massive orebodies with volcanic or plutonic textures. These orebodies commonly have sharp contacts with host rocks and resemble volcanic flows, layered tuff deposits, (e.g., Laco Norte, Chile, Tornos et al., 2016), podiform masses within silicate plutons (e.g., Great Bear Magmatic zone, Canada, Hildebrand, 1986), and pegmatite veins with well-developed epitaxial growth textures (e.g., Pasos Blancos, Chile, Tornos et al., 2016; Iron Springs, USA, Bain et al., 2020). These igneous textures and abundant euhedral magnetite, apatite, and actinolite are key distinguishing features (Sillitoe and Burrows, 2002; Tornos et al., 2023). Most IOA ore bodies are sulphide poor and primarily developed for Fe and minor amounts of chalcopyrite- and arsenopyrite-hosted Cu-Au-Co mineralization. However, recent discoveries of economic light REE mineralization derived from recrystallized primary apatite (e.g., Per Geijer, Sweden, Martinsson et al., 2016) highlight their potential for other critical minerals.

Relative to IOA systems, massive magnetite orebodies in IOCG deposits are more sulphide-rich and tend to consist of structurally controlled replacement zones suggestive of metasomatic processes (Groves, 2010). Alteration in IOCG systems consists primarily of broad regional-scale aureoles of

pervasive Na-Ca alteration (abltie-scapolite-actinolite±garnet; Barton, 2013) that are overprinted by K-Fe-Ca alteration in and around individual deposits. These deposits can form in any host rock and, although typically found in volcanic and sedimentary successions crosscut by a range of intrusive rocks, commonly lack a clear genetic relationship to magmatism of a particular composition (Skirrow, 2022). Most IOCG deposits are mined for Cu and Au in pyrrhotite, pyrite, chalcopyrite, and bornite disseminated in massive magnetite ores. However, these deposits can be enriched in a wide range of elements including Ag, Co, Ni, Bi, Se, Te, In, U, and Mo (Corriveau et al., 2022). Notably, several IOCG deposits feature enrichment in Co-Bi-Au (NICO deposit, NWT, Canada, Burgess et al., 2014; Acosta-Góngora et al., 2015) and U (Olympic Dam, Australia, Reeves et al., 1990; Ehrig et al., 2012).

Iron skarns tend to occur in broad metallogenic belts along convergent margins (Fig. 20; e.g., Yangtze River metallogenic belt, China, Duan et al., 2021; Khaf-Kashmar-Bardaskan volcano-plutonic metallogenic belt, Iran, Golmohammadi et al., 2015) and form alongside gabbroic intrusions in oceanic island arc or back-arc settings (Meinert et al., 2005; Ray, 2013). Most genetic models for iron skarns mirror those of Cu-Au skarn systems. These models involve the exsolution of metal-rich saline fluids from crystallizing magmas at depth, the formation of calcsilicates in carbonate rocks via CO_3^{2-} - SiO_2 exchange, and the precipitation of base-metal mineralization via a decrease in temperature and a shift in fluid pH (Meinert et al., 2005). However, current research suggests that carbonic-sulphate fluids rather than aqueous chloride solutions might play a more important role in iron skarn formation by driving Fe mobility and controlling redox conditions on the deposit scale (e.g., Duan et al., 2021). Similar processes are also inferred in IOA and IOCG deposits.

Iron oxide-apatite deposits typically form in continental arc environments in extensional or transtensional settings (Skirrow, 2022). The characteristic magmatic textures of IOA ores provide clear evidence for an orthomagmatic genetic model in which mineralization represents crystallized Fe-P liquids formed via silicate melt immiscibility driven by the assimilation of sulphate-bearing carbonate rock (Tornos et al., 2023). Evidence for this model includes the common crosscutting relationship between mafic intrusions and evaporite-bearing carbonate strata in many IOA systems and abundant carbonate-sulphate melt inclusions in IOA ores (Bain et al., 2020, 2021). However, IOA systems commonly contain abundant Na-Ca and acid-sulphate alteration, dissolution-reprecipitation textures, and display a mixed sedimentary and magmatic-hydrothermal isotopic signature (e.g., Johnson et al., 2016). These features have led others to invoke contrasting metasomatic (Barton and Johnson, 1996) and magmatic-hydrothermal models (Sillitoe and Burrows, 2002; Reich et al., 2022).

Iron oxide-copper-gold deposits can form in diverse geodynamic contexts but are mainly found in: 1) orogenic settings in previously extended terrains with coeval felsic magmatism (Cloncurry Province, Australia, Williams and

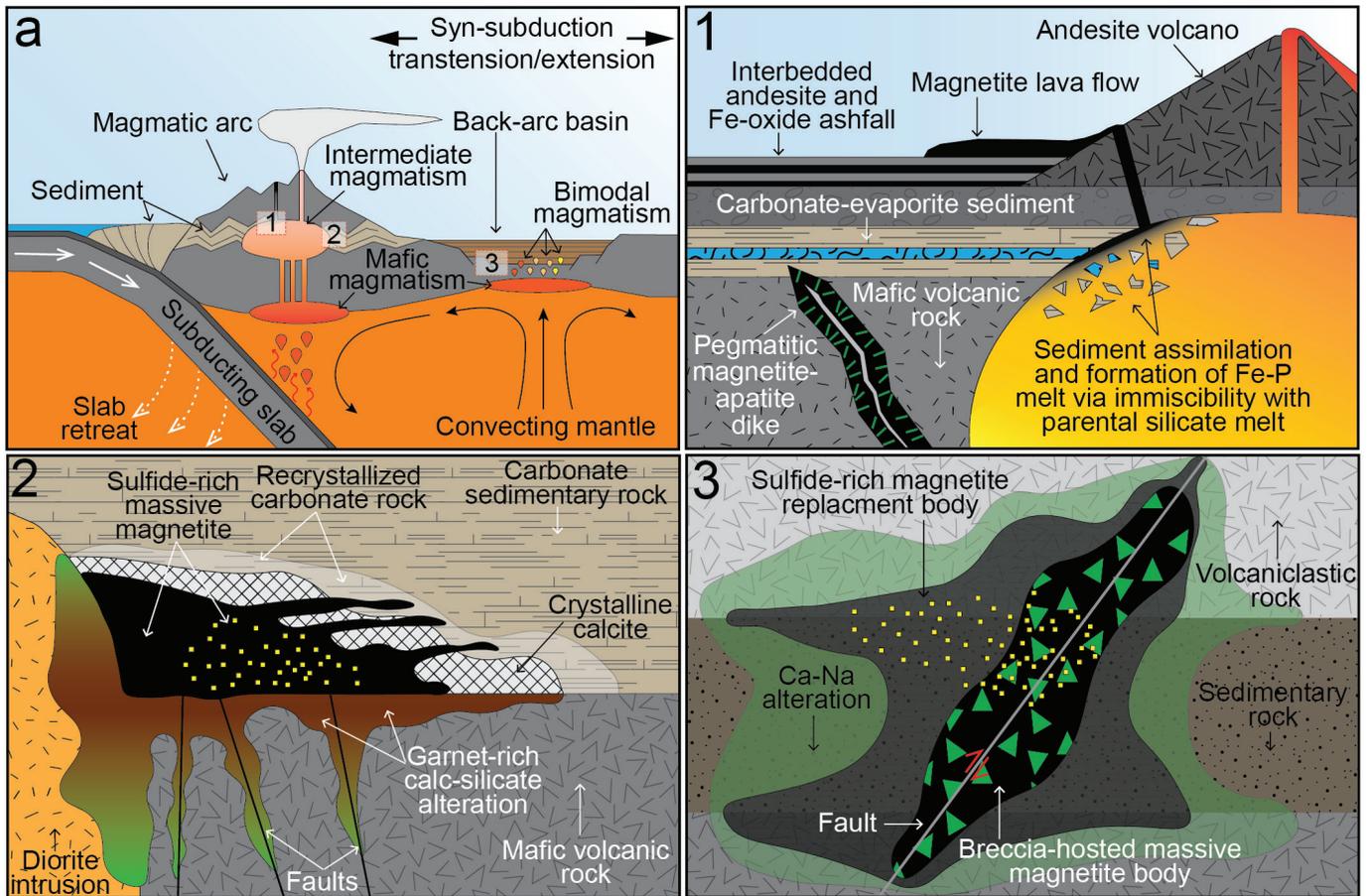


Fig. 20. a) Arc setting for iron skarns ('1'), IOA deposits ('2'), and IOCG deposits ('3'). **1)** Andesite volcanic complex hosting massive IOA ore bodies showing volcanic- and pegmatitic dike-like morphologies. Note the assimilation of evaporite-bearing carbonate sediments by silicate magma at depth and the formation of Fe-P melt via melt immiscibility. This is a representation of the orthomagmatic model for IOA deposits. Other models invoke metasomatic processes particularly when the ore bodies are more like that shown in panel '3'. **2)** Sulphide-rich iron skarn with calc-silicate alteration in the Si-rich volcanic and intrusive host rocks and an envelope of crystalline calcite and recrystallized carbonate rock surrounding the massive magnetite ore. Sulphides are denoted by yellow squares. **3)** Sulphide-rich breccia-hosted IOCG ore body surrounded by a replacement-style ore body and an aureole of Ca-Na alteration. Mineralization is focused along a fault and the distribution of the replacement ore and alteration follows lithologic contacts.

Pollard, 2001; Carajas Province, Brazil, Monteiro et al., 2008); 2) extended post-orogenic settings with bimodal, predominantly felsic, magmatism (Gawler Craton, Australia, Johnson and Cross, 1995), and 3) arc settings where a switch from compression to extension coincides with intermediate magmatism (Great Bear magmatic zone, Canada, Ootes et al., 2017; Andean Province, Chile and Peru, del Real et al., 2018). A range of genetic models exist for IOCG systems. Many recent studies invoke magmatic-hydrothermal processes as the key mechanisms and propose porphyry-like models involving the exsolution of saline, Fe-rich magmatic-hydrothermal fluids from magmas crystallizing at depth and magnetite precipitation via extensive fluid-rock reactions (e.g., del Real et al., 2020; Melfou et al., 2023). The analogy to porphyry-like hydrothermal processes goes further in some models invoking a continuum between IOCG and porphyry deposits, with IOCG mineralization representing the basal expression of regional hydrothermal systems (Mumin et al., 2010; Richards

and Mumin, 2013). These models are supported by the textures and the geochemical and stable isotope (S, O, C, Fe) signatures of ore and alteration mineralogy. However, these data sets also consistently reflect inputs from carbonate and evaporitic sedimentary sources. This has led others to attribute IOCG formation to the circulation of fluids of sedimentary or near-surface origin and extensive leaching of Fe from mafic host rocks by (e.g., Johnson and Barton, 1996).

Iron skarns are distributed in a northwest-trending belt extending from Vancouver Island and Texada Island to Haida Gwaii (Fig. 21; Ray, 2013) and are currently being investigated as part of the critical minerals program at the Survey (Fig. 22). Clear examples of IOA deposits in British Columbia are rare with two possibilities including the apatite-rich magnetite veins that crosscut the Heffley Creek Alaskan-type mafic-ultramafic pluton (Glen Iron and Magnet deposits, described by Ray and Webster, 2000) and the base of the New Afton porphyry Cu-Au deposit (described by Logan and Mihalynuk, 2005;

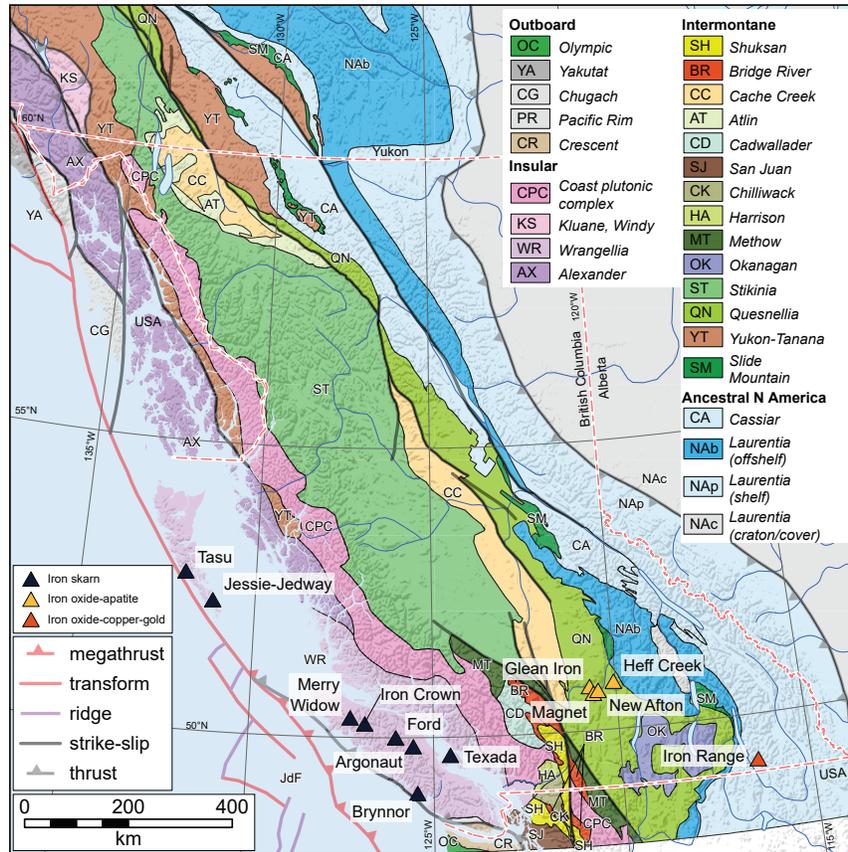


Fig. 21. Iron skarn, possible iron oxide-apatite (IOA), and possible iron oxide-copper-gold (IOCG) deposits in British Columbia. Terranes after Colpron (2020).

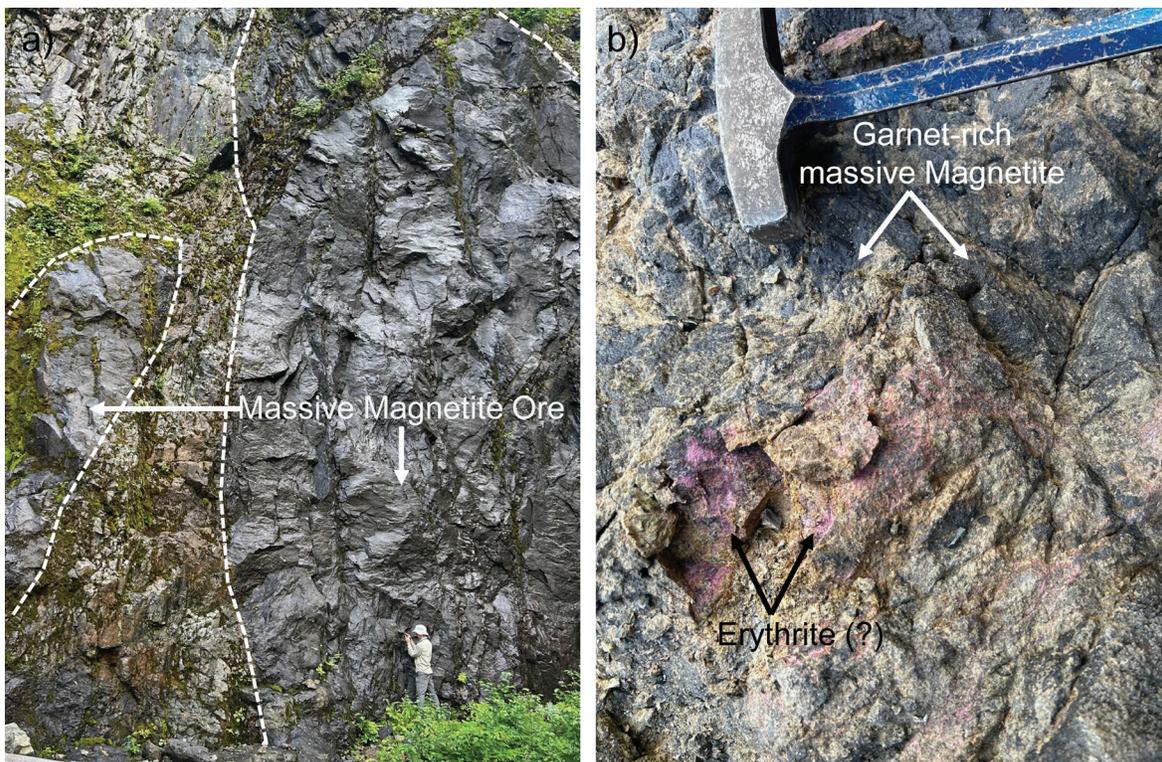


Fig. 22. a) Massive magnetite ore body along the southern wall of the Merry Widow mine, Vancouver Island. Not the sharp contacts between the ore and the host rocks. b) Erythrite-bearing (?), garnet-rich, podiform magnetite mineralization from northern Texada Island.

Hall and May, 2013; Thomas, 2021). The one possible IOCG example in the province would be replacement-style magnetite clusters along the Iron Range fault zone in Belt-Purcell basin (Mesoproterozoic) of south-central British Columbia (Stinson and Brown, 1995; Galicki et al., 2012). However, IOCG- and IOA-like mineralization commonly overprints or is spatially associated with the deep and peripheral areas of alkalic porphyries and base-metal skarns and could host additional Co-Bi- and REE-bearing mineralization, an idea that is currently being evaluated.

6. Discussion

British Columbia is already an important critical mineral producer. British Columbia is Canada's largest producer of Cu, only producer of Mo, mines Mg, and recovers Zn, Ag, and Pb. In addition to Pb and Zn, British Columbia smelters process metals not mined in the province: Al at the Rio Tinto smelter in Kitimat; and Ge, Cd, and In at the Teck Resources facility in Trail (Fig. 23). Several mine development and proposed mine projects in British Columbia could produce elements on Canada's critical minerals list as well as Ag, a metal that is typically classified as precious but with important applications in renewable energy such as for solar cells (Fig. 24). These proposed mines include Aley (Nb), Bull River (Cu, Ag), Galore Creek (Cu, Ag), Kemess Underground (Cu, Ag), Kemess East (Cu, Ag), Kitsault (Mo, Ag), KSM (Cu, Ag, Mo), Kutcho (Cu, Zn, Ag), Record Ridge (Mg), and Ruddock Creek (Zn).

The province also has many advanced projects with National Instrument 43-101 (NI 43-101)-compliant defined resources that include critical mineral elements (Fig. 24). Advanced projects include Akie (Zn, Pb, Ag), Berg (Cu, Mo, Ag), Chu Chua (Cu, Zn, Ag), Decar Nickel District (Ni, Co), Fox Tungsten (W), Yellowhead (Cu, Ag), Jersey-Emerald (W, Mo), Kitsault Valley-Dolly Varden (Ag), Kitsault Valley-Homestake Ridge (Ag, Cu), Kwanika (Cu, Ag), Lac La Hache (Cu, Ag), North Island (Cu, Mo, Re), Ootsa (Cu, Mo, Ag), Poplar (Cu, Ag, Mo), Revel Ridge (Zn, Ag), Ruby Creek (Mo), Schaft Creek (Cu, Mo), Silver Queen (Ag, Zn, Cu), Silvertip, (Ag, Zn, Pb), Stardust (Cu, Ag), Tatogga (Cu, Ag), Turnagain (Ni, Co), Wicheeda (REE), and Woodjam (Cu).

As British Columbia develops its Critical Mineral Strategy, new geoscience will be the foundation for establishing new opportunities. Ongoing geoscience research by the Survey is methodically assessing mineral systems to understand the spatial and temporal distribution of critical minerals at regional and deposit scales. In the short-term, clarifying by- and co-production possibilities of critical minerals not being recovered from current base and precious metal mines will likely be important. In the long-term, providing foundational geoscience data and developing novel exploration techniques will encourage discoveries and enhance exploration for underexplored mineral systems.

The digitization (direct analog-to-digital conversion of data and documents) and digitalization (enabling these data

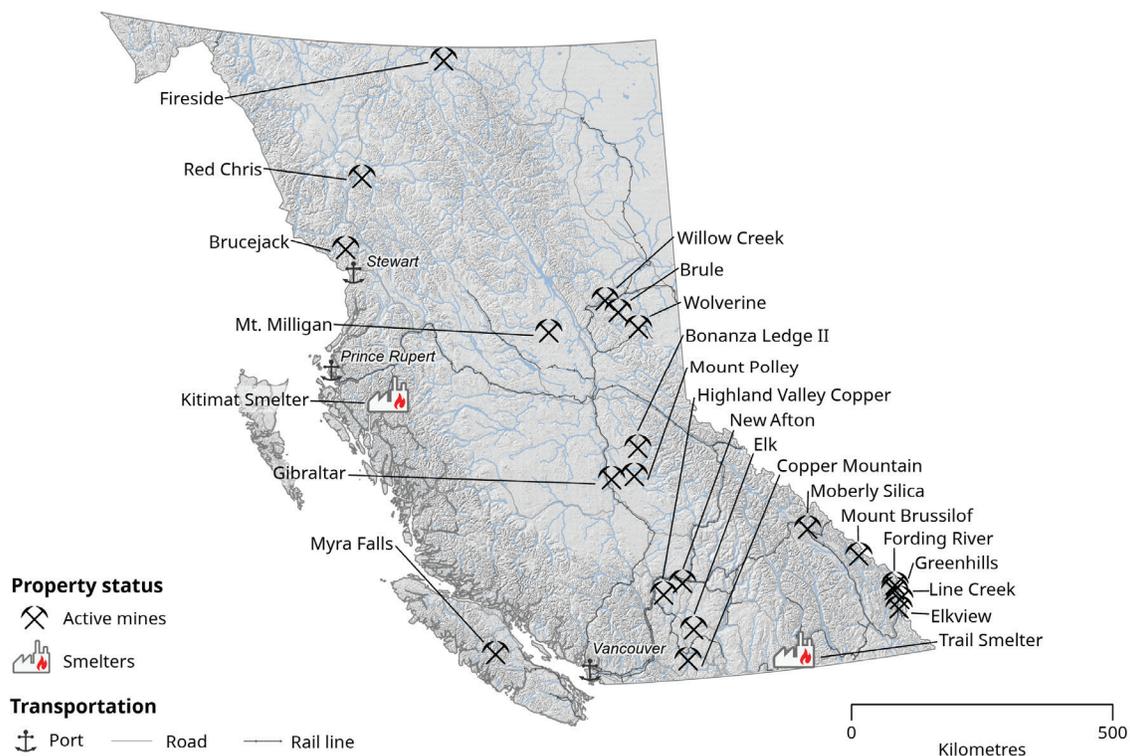


Fig. 23. Operating metal, coal, and industrial mineral (Fireside, Moberly, Mt. Brussilof) mines and smelters in British Columbia, 2022. From Hickin et al. (2023).

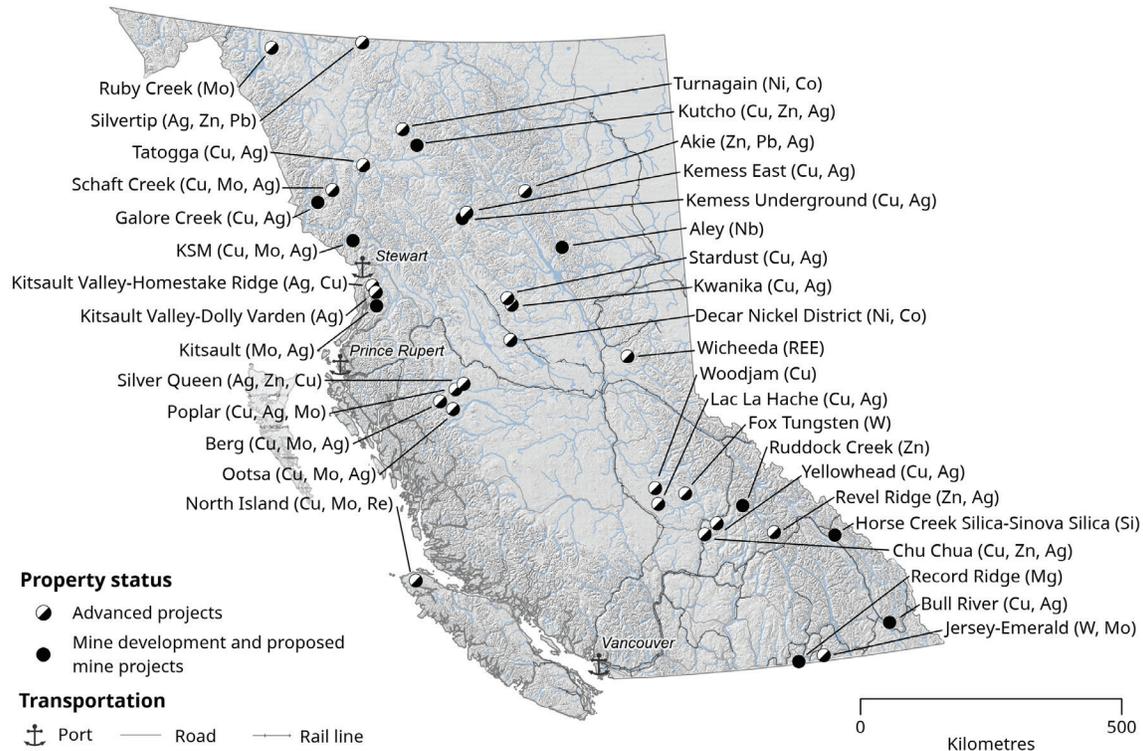


Fig. 24. Mine development and proposed mine projects and advanced projects in British Columbia, 2023, with critical minerals indicated in parentheses. From Hickin et al. (2023).

to be compatible and usable across information systems) of geoscience information is another essential activity for capitalizing on the global investment in critical minerals. Advances in computational power and sophistication have enabled innovative analysis of new and existing geochemical, geophysical, and geological data that has accelerated the recognition of patterns, trends, and the understanding of mineral systems. The expansion of digital data and the improvement of data-driven analytics is enabling the next generation of mineral potential modelling in British Columbia. Establishing the essential metal sources, transport pathways, and chemical and physical traps for a mineral deposit that can be mapped or detected, provides the foundation on which to evaluate British Columbia's mineral potential. The ability to digitally, statistically, spatially, and temporally interrogate provincial geoscience data allows probability models to be constructed that highlight potential mineral districts. These models are essential to ensure that decisions made by governments, rightsholders, stakeholders, and investors are appropriately informed so that the choices maximize the benefit to society.

7. Conclusion

A long and multifaceted tectonic history has endowed British Columbia with a host of mineral systems. Each of these systems form in different ways and have specific critical mineral endowments. Porphyry systems, an immediate consequence of magmatic arc evolution, provide the most significant

critical mineral resources in British Columbia. The principal commodity in most porphyry deposits is Cu, and porphyries are the only deposit type to contain significant Mo. Porphyry deposits in British Columbia may also contain appreciable Au and Ag and, to a lesser extent, the PGE, Re, Se, and Te. In the more Mo-rich porphyry deposits, Li, Nb, REE, Rb, Ta, and Sn may be present in recoverable quantities. Volcanogenic massive sulphide deposits represent another important system because they contain most of the Co and Zn in the province. Deep-water basin sedimentary exhalative systems are significant hosts to Pb, Zn, and Ag, could conceivably supply Bi, Ge, In, Sn, and W. Similarly, platformal Mississippi Valley systems supply Pb, Zn, and Mg, but have the potential to contain Ba, Ga, Ge, In, REE, and F. Magmatic sulphides represent a significant system that may host economic concentrations of Ni, PGE and Co. Carbonatites are also important because they are the only hosts to significant Nb and Ta in British Columbia and are the primary global source of REEs. IOA and related deposits may represent under-recognized potential in British Columbia for critical minerals, a hypothesis that continues to be tested.

Many greenhouse gas-reducing strategies require critical minerals that must be mined. British Columbia is presented with a generational opportunity to supply some mine products that can contribute to addressing the climate crisis while, at the same time, benefitting the provincial economy. With abundant hydroelectric power and the potential to use this power to produce critical minerals, British Columbia may be able to

provide materials with a substantially lower carbon footprint than jurisdictions that rely on fossil fuels.

The British Columbia Geological Survey is refining mineral systems models that may host critical minerals and developing exploration techniques that could lead to new discoveries and expand existing resources. By increasing awareness of critical mineral opportunities for the exploration and mining industries, and by enhancing the critical mineral knowledge base, the province seeks to encourage investment that could lead to British Columbia being a significant supplier of the raw materials necessary to support a low-carbon future.

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