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# Cobalt mineralogy at the Iron Creek deposit, Idaho cobalt belt, USA: Implications for domestic critical mineral production

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## ABSTRACT

**Current U.S. policies aim to establish domestic supply chains of critical minerals for the energy transition. The Iron Creek deposit in the Idaho cobalt belt (ICB) is one of the most promising cobalt (Co) targets. Our case study illustrates the importance of mineralogy in strategic evaluations of critical mineral potential. Most of the Co at Iron Creek occurs as Fe substitution in pyrite, with lattice-bound and inclusion-hosted Ag, As, Bi, Ni, Pb, Se, Te ± trace Au and Sb. Cobalt also occurs in minor cattierite-vaesite. The Co minerals are intergrown with Co-poor chalcopyrite hosting Cu ± minor In and Zn. Worldwide, most Co is recovered from deposits mineralogically distinct from the ICB, and the United States currently lacks infrastructure to recover this Co and its associated metals. ICB ore minerals could be processed by autoclave, roaster, smelter, bioleach, or heap leach. Recovery of the Ag, As, Au, Bi, In, Pb, Se, Te, and Zn would be costly by autoclave, and construction of a custom smelter for ICB ores is likely uneconomic, so these elements would become waste irrespective of criticality. The Co-Fe and Co-As sulfide minerals are most suitable for Co and Ni recovery by a hydrometallurgical autoclave process, with potential pretreatment of cobaltiferous pyrite/arsenopyrite in an inert-atmosphere roaster, in new domestic or anticipated international facilities. The ICB is the second largest known Co resource in the United States. Consideration of ore mineralogy in the ICB is essential in strategies for domestic production.**

## INTRODUCTION

Policymakers in the United States and worldwide have called for net-zero carbon emissions by 2050 to slow the rate of global warming. The transition to renewable energy will require an increase in mineral and metal production (Hund et al., 2020; Sovacool et al., 2020; Watari et al., 2020). By 2050, demand is forecasted to increase by more than 500% for cobalt (Jowitt and McNulty, 2021), a "critical mineral" used in rechargeable batteries. Similar projections have been made for commodities required for renewable energy systems (Hund et al., 2020; Nguyen et al., 2021), including a 140% increase in demand for copper by 2050 (IEA, 2022). Cobalt and other elements on the U.S. Critical Minerals list (USGS, 2022a) are vulnerable to supply disruptions due to the lack of geopolitical diversity in production as well as net import reliance. In 2021, the United States mined 0.4% of the world's Co. Over 70% was mined from sedimentary-hosted Cu-Co deposits in the Democratic Republic of Congo (USGS, 2022b), where artisanal mining by children has led to scrutiny of high-tech Co buyers and interest in new markets for ethically sourced Co (Jamasmie, 2021).

Current U.S. policies aim to establish domestic supply chains for production, refining, and recycling of critical minerals (The White House, 2022). The Idaho cobalt belt (ICB) is one of the most prospective locations for domestic Co (Fig. 1; Holtz, 2022). The northwest-trending belt hosts at least 45 known occurrences of Co + Cu ± Au in central Idaho. The United States currently lacks the infrastructure to recover Co and associated metals from Co-As and Co-Fe sulfide minerals in the ICB's Blackbird, Black Pine, Ram, Sunshine, and Iron Creek deposits (Fig. 1). The methods, recoverable metals, and costs are directly linked to the ore mineralogy. We documented the ore mineralogy, textures, and metal geochemistry at Iron Creek, using the case study data to compare viable recovery methods for the ICB. We also mapped worldwide Co production infrastructure according to mineralogy, and we bring these concepts together to show how the ICB could fit into global metal supply chains.

## STUDY AREA AND METHODS

The Iron Creek deposit was originally explored for copper and cobalt in the 1970s, focused on stratabound sulfide-rich zones in argillite-siltite and quartzite metasedimentary rocks of the Apple Creek Formation in the southwest Belt-Purcell basin. Hydrothermal mineralization likely occurred in the mid-Mesoproterozoic, with possible magmatic-hydrothermal or metamorphic remobilization in the late Mesoproterozoic or Cretaceous (Saintilan et al., 2017). The sulfide mineralized zones are mostly conformable with bedding and occur as massive lenses or disseminations, along with stringers, shearing, and brecciation (First Cobalt Corp., 2019). Most of the Cu enrichment is in the shallow part of the deposit, whereas the deeper portion is dominated by Co. Based on an underground mining scenario, Electra Battery Materials (formerly First Cobalt) defined an indicated resource of 2.2 million metric tonnes at 0.32% cobalt equivalent (0.26% Co and 0.61% Cu), equating to ~6000 tonnes of contained Co and 13,000 tonnes of contained Cu, plus an inferred (less certain) resource of 5700 tonnes of Co and 18,000 tonnes of Cu (First Cobalt Corp., 2019).

We characterized the ore mineralogy at Iron Creek using thin section petrography, scanning electron microscopy (SEM), SEM-based automated mineralogy, micro–X-ray fluorescence (μXRF) mapping, and laser ablation–inductively coupled plasma–mass spectrometry

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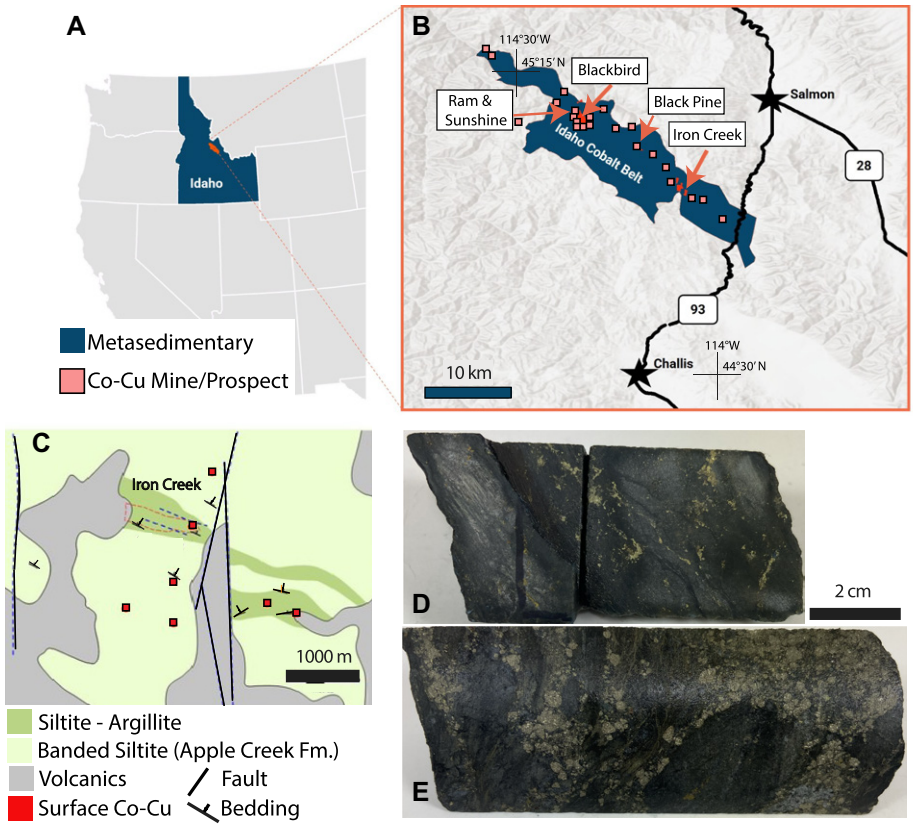


**Figure 1. (A–C) Iron Creek deposit location, Idaho cobalt belt (Electra Battery Materials, 2022). (D–E) Drill cores from (D) Co and (E) Co-Cu ore zones.**

(LA-ICP-MS) mapping and spot analyses (Supplemental Material[1]) on five high-grade drill-core samples (up to 0.5% Co and 4.6% Cu) from the Co-Cu and Co zones at Iron Creek. We drew from industry and government data to map the mineralogy, processing, and refining of global cobalt ores in comparison to ores in the ICB.

## RESULTS

### Ore Mineralogy

The investigated ore samples from Iron Creek are mostly composed of pyrite (up to 94%), ranging from 10 μm to 2 mm (maximum dimension; Figs. 2A and 2B). The pyrite displays a wide range of textures, including large grains with fractures and inclusions, clusters of anhedral or euhedral fine grains, spongy resorbed grains, and spongy or sharply zoned overgrowths. The interstices are commonly filled with chalcopyrite, up to 8% in the Co ore zone (Fig. 2C) and 28% in the Co-Cu ore zone (Fig. 2D). The ores also contain up to 2% of a 10–100 μm sulfide mineral in the Ni-Co cattierite-vaesite solid solution series, associated with pyrite and iron oxides (Fig. 2B). The matrix is quartz (1%–70%), Fe-(Mn-) oxides (up to 26%), chlorite (2%–20%), muscovite (up to 10%), biotite (up to 2%), and apatite (up to 2%; Figs. 2A–2B; Supplemental Materials).

### Metal Enrichment

The majority of the Co enrichment is in overgrowths, cracks, and patchy alteration of the pyrite (Fig. 2). The pyrite contains up to 6 wt% Co. Most of the Cu is in Co-poor chalcopyrite (Figs. 2 and 3). High concentrations of Co also occur in the minor cattierite-vaesite. The coarser textural styles of pyrite have Co-poor cores containing up to 1 wt% Ni, encapsulated by higher Co in concentric or patchy zones (Fig. 2). The Co enrichment occurs throughout the smaller grains. There is a negative correlation between Fe and Co in the pyrite, indicating direct substitution of Co for Fe in the crystal lattice (Fig. 3). The spatial distribution of As is similar to Co in the pyrite, although there is four times as much Co compared to As (Fig. 3). The pyrite contains other trace elements in two modes: in the crystal lattice or in <10 μm inclusions. The inclusions contain up to 17% Cu and ~80 ppm Ag, 3000 ppm Bi, 3000 ppm Pb, 800 ppb Se, and 1400 ppm Te ± trace Au and Sb (Figs. 2 and 3). The chalcopyrite contains less than 100 ppm Co, displays no internal zonation, and is commonly partially replaced by or intergrown with Fe-(Mn-) oxides. The chalcopyrite contains up to ~1000 ppm Zn, ~350 ppm Se, ~100 ppm Ag, and ~34 ppm In.

## DISCUSSION

Iron Creek demonstrates the typical ICB association between chalcopyrite and Co-Fe or Co-As sulfides. Our data show that cobaltiferous pyrite and catterite-vaesite are intergrown with chalcopyrite in some zones, although much of the Cu is concentrated in areas with less Co in pyrite. At Blackbird, Co occurs in bedded cobaltite (CoAsS) intergrown with variable amounts of chalcopyrite, native Au, Bi minerals, xenotime, and minor pyrite (Slack, 2012). At Ram and Sunshine, the ore consists of disseminations, blebs, and stringers of cobaltite and chalcopyrite with minor pyrite (Sletten et al., 2020), minor native Au, Ag and Bi, arsenopyrite, pyrite, and marcasite (Eiseman, 1988). The Cu/Co ratio is higher at Black Pine, where bedded chalcopyrite occurs with cobaltiferous arsenopyrite (FeAsS), minor cobaltite, and anomalous Au, Bi, and light rare earth elements (LREEs; Bending and Scales, 2001). At Black Butte in Montana, a similar ore style hosts chalcopyrite, cobaltiferous pyrite, siegenite ($CoNi_2S_4$), and cobaltite (Graham et al., 2012).

Worldwide, most cobalt is produced as a by-product of Cu and Ni production (Nassar et al., 2015; Hitzman et al., 2017; Slack et al., 2017; Horn et al., 2021) from deposits with Co mineralogy distinct from the ICB (Fig. 4). In the Democratic Republic of Congo and Zambia, cobalt occurs as carrolite, $Cu(Co,Ni)_2S_4$, which is smelted or roasted alongside chalcopyrite. The weathering product heterogenite, CoO(OH), is then leached. Laterite deposits have lower Co grades than the ICB; Co and Ni are mostly recovered from Mn- and Fe-oxyhydroxides by acid leaching in an autoclave. Magmatic Ni-Co sulfide deposits have Co grades that are 30% of the ICB. Pentlandite, $(Fe,Ni,Co)_9S_8$, is processed by smelters optimized for Ni. Much of the Co is lost to slag, due to the relative oxidation potentials of Co and Ni (Reznik, 1993). Minor amounts of Co are recovered from Ni sulfides mined in Michigan and smelted in Canada (USGS, 2022b). At the Stillwater magmatic sulfide deposit in Montana, platinum group metal smelter mattes are refined to produce by-product nickel sulfate that contains minor Co (Stillwater, 2016). Magmatic sulfide Ni-Cu-Co deposits in Minnesota are not currently mined.

Cobaltiferous pyrite is known outside the ICB in a range of deposit types. It occurs, but is not currently exploited, at some volcanogenic massive sulfide (e.g., Outokumpu, Finland; Ducktown, Tennessee) and black shale deposits

[1]Supplemental Material. Detailed methods, materials, and data tables. Please visit https://doi.org/10.1130/GEOL.S.22595941 to access the supplemental material, and contact editing@geosociety.org with any questions.

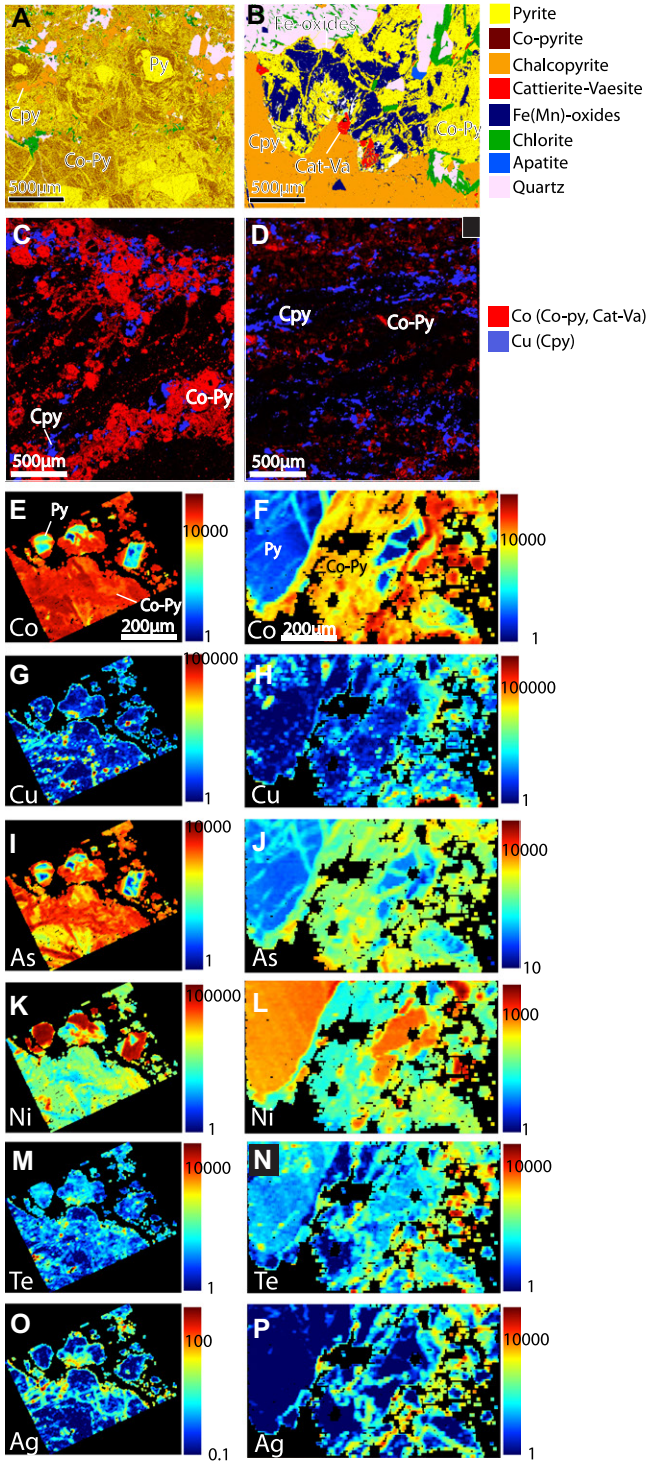


**Figure 2. Mineralogy and chemistry of Iron Creek ores. (A, B) Examples of scanning electron microscope–based automated mineralogy false-color images used to determine modal abundances (Supplemental Materials [see text footnote 1]). (C, D) Mapping micro–X-ray fluorescence element distribution in Co-ore (left) and Co-Cu ore (right). (E–P) Pyrite trace elements mapped by laser ablation–inductively coupled plasma–mass spectrometry (ppm).**

(Talvivaara, Finland; Horn et al., 2021). At Kasese in Uganda, Co was produced from cobaltiferous pyrite in sedimentary-hosted Cu-Co ores by bioleaching from 1998 until the mid-2000s (Gericke et al., 2009). In Australia, cobaltiferous pyrite occurs in metamorphosed stratabound deposits 25 km from the Broken Hill Pb-Zn-Ag deposits. A demonstration roaster is under construction to produce Co by decomposing this pyrite to pyrrhotite in an inert (e.g., nitrogen) atmosphere (Cobalt Blue, 2020).

Cobalt could be recovered from ICB ore minerals by autoclave, roaster, smelter, bioleach, or heap leach (Fig. 4), but new infrastructure is needed to do so. In the early 1900s, Co and Cu concentrates from the Blackbird deposit were processed by an autoclave in Garfield, Utah (Mitchell, 1957; USGS, 2009). The facility no longer processes Co, and Blackbird is a Superfund site due to metal contamination of waterways. There are no commercial Co autoclave processing facilities currently operating in the United States, although one is under construction in Missouri. The mining company Jervois commenced mining at the Ram deposit in 2022 and is building a Co-Ni autoclave in Brazil for its ICB cobaltite concentrates (https://jervois-global.com/company/). Electra Battery Materials plans to send Iron Creek concentrates to the Co-Ni autoclave being refurbished in Ontario, Canada (First Cobalt, 2019). At Black Butte, concentrates will be shipped to a Cu smelter, and the Co minerals will be left in waste (Sandfire, 2020).

Ideally, we propose the following to treat the majority of ICB ores: (1) separation of most chalcopyrite from the ores for shipping to one of the three U.S. Cu smelters, and (2) processing of Co minerals by hydrometallurgical autoclave, in new domestic or existing Canadian facilities, with pretreatment of the cobaltiferous pyrite/arsenopyrite in an inert-atmosphere roaster.

Based on the mineral chemistry of our samples, we calculate that an Iron Creek sulfide mineral concentrate of chalcopyrite, pyrite, and cattierite-vaesite would contain ~2.5–3.5% Co. The presence of chalcopyrite would displace production of more valuable Co in a throughput-limited autoclave. We suggest that chalcopyrite should be separated from ICB Co ores for more efficient Cu recovery by a smelter. In some low-Co zones of the ICB, this could be achieved through selective mining of chalcopyrite ores. Mixed Co-Cu zones would require crushing and grinding to ~10 µm to liberate chalcopyrite from the Co minerals, leading to additional cost, since the typical particle size for sulfide mineral flotation is coarser (75–125 µm). After grinding to liberate chalcopyrite from Co-As and Co-Fe sulfides, differential flotation could be applied to produce a chalcopyrite concentrate (Shengo et al., 2019). We estimate that removing chalcopyrite could theoretically upgrade the Iron Creek concentrate to ~5% Co.

The trace elements in inclusions within the pyrite (Ag, Au, Bi, Cu, Pb, Sb, Se, and Te) could be recovered in a precious metals refinery, if the inclusions could be liberated. Our textural observations suggest that this liberation would require even finer grinding than needed to liberate the chalcopyrite, followed by novel separation methods. Unfortunately, the value in the inclusions may not merit the costs or energy, since crushing and grinding for particle size reduction have historically ranked the mining industry among the largest energy consumers in the United States (Pellegrino et al., 2004).

Smelter production of Co and Cu from the ICB would require a purpose-built facility, which could also recover precious metals. Many of the lattice-bound trace elements would be more difficult or expensive to recover in an autoclave and would likely become waste (e.g.,

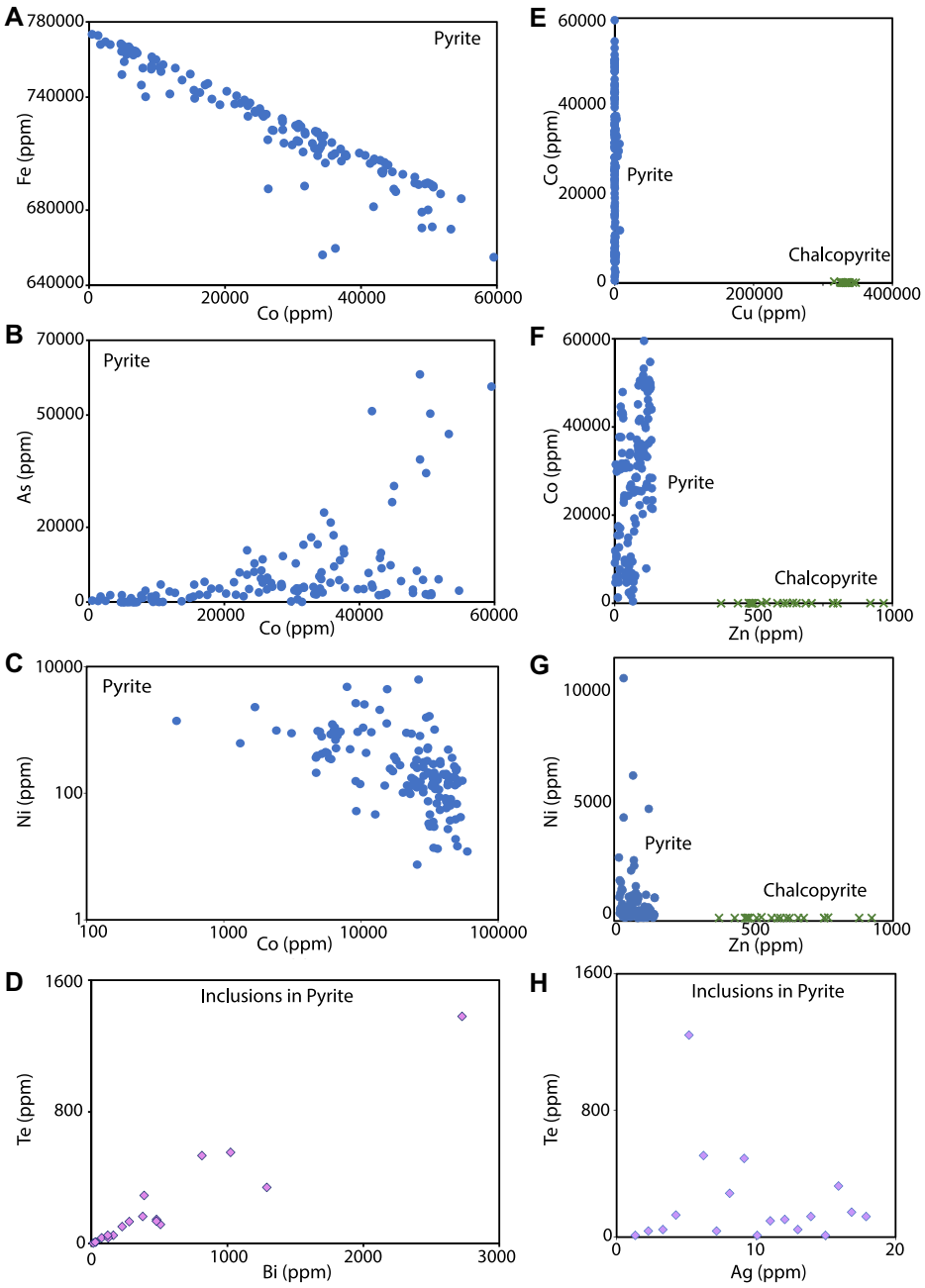


**Figure 3. Metal concentrations in pyrite and chalcopyrite in samples from Iron Creek, from laser ablation–inductively coupled plasma–mass spectrometry spot analyses.**

the pyrite-hosted Ag, Au, **As**, **Bi**, Pb, **Sb**, and **Te** and the chalcopyrite-hosted **In** and **Zn** at Iron Creek; bolded are U.S. critical minerals). Smelting of Ag, Au, In, Se, and Te can create a material stream from which they can be technically and economically recovered (Green, 2006). Some critical minerals such as Te are almost exclusively a by-product of smelting (Smith et al., 2019). A new smelter would be needed, since existing Cu-Co smelters in Africa and China are designed for a feed with less As and less pyrite than ICB ores (Khoso et al., 2021). There are three Cu smelters in the United States, but none can recover In, Zn, or Co (Zhai et al., 2011). The combined resources in the ICB are unlikely to justify the cost of constructing a new smelter customized to maximize recovery of the elements present in these deposits.

Iron Creek and Ram constitute the only defined resources in the ICB (First Cobalt Corp., 2019; https://jervoisglobal.com/company/). Combined, the currently known resources at the two deposits would meet about 1 yr of U.S. demand for Co in 2050, and about a week of demand for Cu (assuming projected increases in demand relative to the quantities consumed in 2022; USGS, 2022b). Other deposits in the ICB are in early exploration stages, and the total resource is likely larger. We used the elemental ratios in our data to estimate that the indicated resource at Iron Creek contains ~121 tonnes Ni, 37 tonnes Bi, 24 tonnes Zn, 18 tonnes Te, and 0.8 tonnes In. This equals nearly a year of current domestic consumption of Te; days to weeks for Ni, Bi, and In; and a negligible period for Zn (USGS, 2022b). Recovery of these commodities by zero-waste mining would require a framework that optimizes environmental and social outcomes rather than economics. The ICB is a potential testing ground for new approaches to domestic mining, since its Co endowment is second only to that in Minnesota, where several potential critical mineral projects face permitting and environmental challenges.

## CONCLUSIONS

Our case study at Iron Creek illustrates the importance of mineralogy and mineral chemistry in strategic evaluations of global metal supply chains. Domestic cobalt production from the ICB is technologically attainable, but recovery and refining would require mineralogically appropriate infrastructure currently only available outside the United States. The Co and Ni in ICB cobaltite and cobaltiferous iron sulfides could be recovered by a hydrometallurgical autoclave process. Copper production from the ICB would be more efficient by smelting after separation of the chalcopyrite. Construction of a custom smelter for the ICB is unlikely to be economic, so the inclusion-hosted Ag, As, Au, Bi, In, Pb, Se, Te, and Zn at Iron Creek will likely become waste irrespective of the potential processing options and criticality. The ICB cannot meet projected domestic demand for Co, although production from this district could bolster U.S. stockpiles against insecurity. Supply of mineral commodities such as Co for the energy transition will be governed by mineralogical constraints in economic, social, environmental, and geopolitical contexts.


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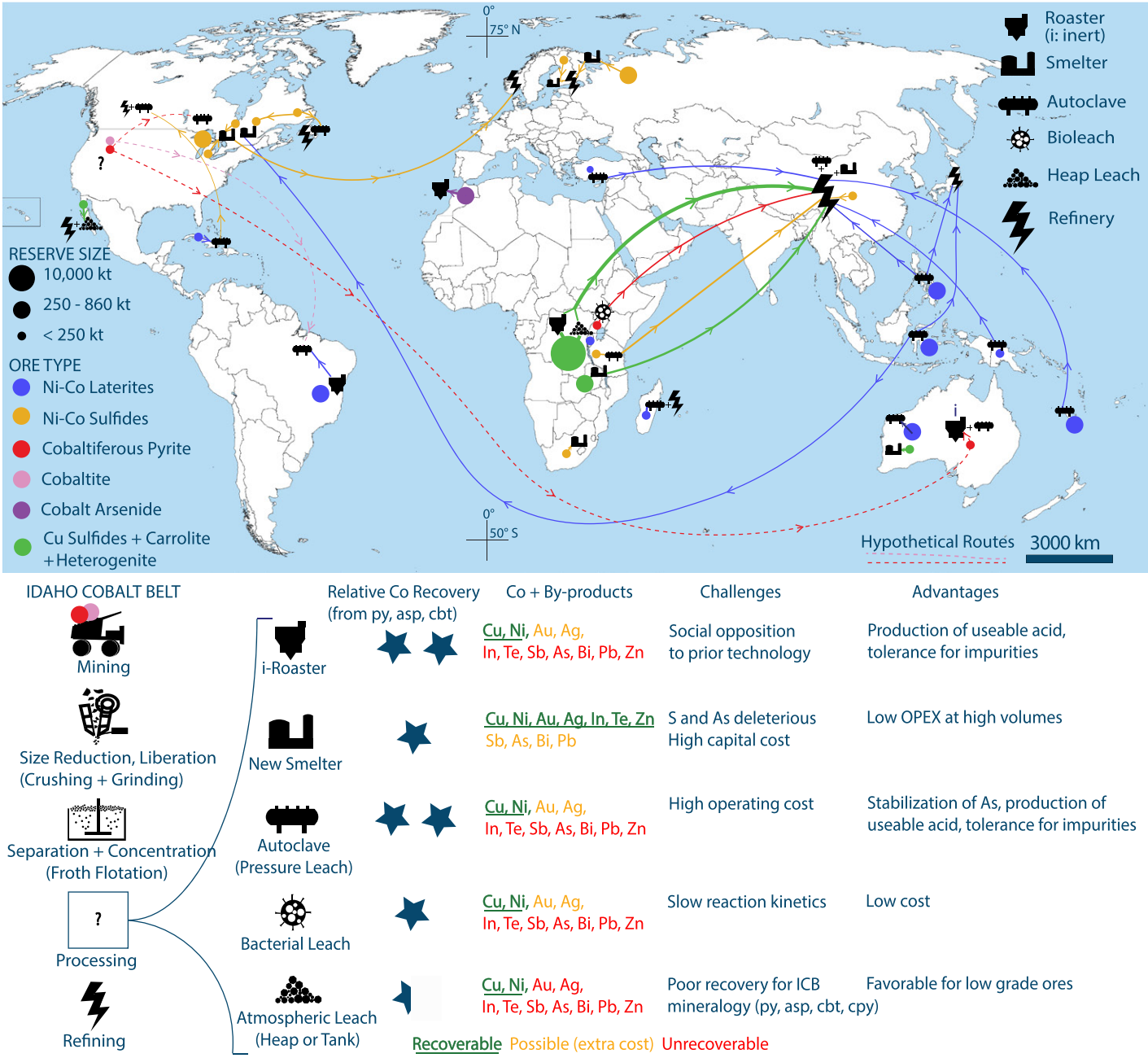


**Figure 4. Global mining and processing of cobalt by mineralogy, showing dashed arrows and potential flowsheets for Idaho cobalt belt (ICB) production (for map input data, see Supplemental Materials [see text footnote 1]). Py—pyrite; asp—arsenopyrite; cbt—cobaltite; cpy—chalcopyrite.**


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