

Mine Tailings Offer Few Opportunities for Critical Mineral Recovery

Prospects Based on Elemental Concentrations



BY PETER COOK

EXECUTIVE SUMMARY

Interest in reprocessing discarded mine tailings for critical minerals has skyrocketed among policymakers. The prospect of “re-mining” has stimulated significant investment—even discouraging policies supportive of conventional mining under the impression that tailings alone could soon meet much of U.S. demand.

However, overcommitment risks material consequences for the future of U.S. critical mineral supply chains. Indeed, tailings recovery of accessory elements largely remains a hypothetical prospect.

Some opportunities for tailings recovery do exist. Specifically, we find 16 accessory element-deposit type combinations that could offer economically feasible prospects. However, for many other important critical mineral needs like antimony, chromium, lithium, manganese, and tin, we emphasize that mine tailings are not likely to yield any economic or significant recovery potential.

Policymakers must recognize mine tailings as a limited, supplemental source of critical minerals given low concentrations and the likely prohibitively high energy and chemical inputs needed to recover them, altogether offering low economic feasibility.

KEY FINDINGS

(1) Only in rare circumstances will mine tailings offer opportunities to unlock new production of some critical minerals. Initiatives to recover critical minerals from mine tailings therefore should not substitute policy support for conventional mineral resources.

The feasibility of reprocessing mine tailings for critical minerals varies element by element and site by site, but prospects in general are low. For the majority of critical minerals including antimony, chromium, lithium, manganese, and tin, potential production from mine tailings is likely zero.

(2) Technological improvements in mineral recovery are unlikely to improve economic feasibility. Concentrations near or below crustal abundances for many critical minerals indicate that tailings are no more enriched than ordinary sediment, like garden soil. In principle, mine waste containing the same mineral content as ordinary crustal material may not even warrant consideration as a critical mineral resource.

(3) It is unlikely that active mines unknowingly throw away critical minerals. Few deposit types contain accessory elements at grades comparable to primary ores and those that do reflect well-established geological associations rather than novel enrichment. This indicates that economic feasibility, not undiscovered potential, poses the chief barrier to recovery.

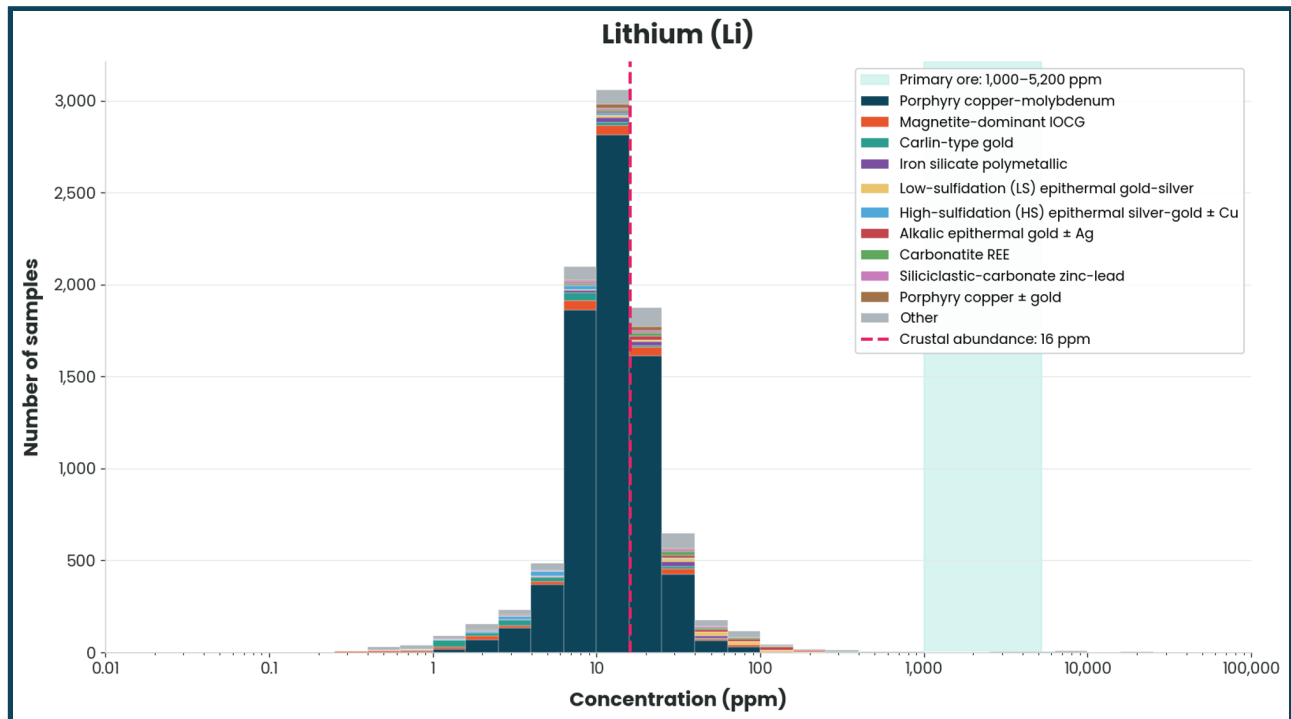


Figure 1: Lithium in ore samples across all deposit types that do not target lithium occurs at concentrations no different than ordinary rock, making economic recovery from tailings essentially impossible (typical economic range shaded in light blue).

NOTABLE TAILINGS PROSPECTS

Our report highlights just 16 cases where accessory elements (i.e., commodities a mine does not target) may occur in tailings at concentrations exceeding their primary ore grades in other deposits. Most of these prospects, however, exhibit small sample sizes and require further investigation. This leaves just five cases with a potentially more robust economic case for tailings recovery.

Recovery may be feasible at lower concentrations than considered here. However, comparison to known economic grades offers a first order assessment of prospects with concentrations above crustal abundances.

We discuss prospects for recovering additional amounts of elements that mines targeted but did not fully recover in a separate discussion below. We do not address mineralogical barriers that may complicate the feasibility of recovering even elevated concentrations.

Element	Deposit Type	n	Median Grade (ppm)	Economic Grade (ppm)
Zirconium	Bauxite	329	1,041	800
Hafnium	Bauxite	329	27	16
Titanium	High-sulfidation epithermal Ag-Au±Cu	296	5,091	5,000
Arsenic	Collapse breccia pipe uranium	71	3,082	2,000
Copper	Collapse breccia pipe uranium	71	4,197	1,500
Arsenic	Breccia pipe copper	12	7,786	2,000
Tungsten	Porphyry tin	7	13,091	800
Zinc	Distal-disseminated silver-gold	6	36,773	31,000
Arsenic	Porphyry tin	4	25,636	2,000
Copper	Porphyry tin	4	22,981	1,500
Copper	Vein tungsten	2	101,886	1,500
Silver	Vein tungsten	2	221	70
Tantalum	Vein tungsten	1	255	180
Titanium	U-M layered intrusion Ni-Cu-PGE	1	5,909	5,000
Arsenic	Vein tungsten	1	2,509	2,000
Yttrium	Vein tungsten	1	358	250

Table 1. Deposit types that exhibit concentrations of accessory elements (i.e., elements that mines do not recover) exceeding those elements' economic grade of primary ores in other deposits. The median grade of each accessory element/deposit type distribution offers a crude proxy of mill feed grades which in turn indicates the bulk tailings concentration of each accessory element. Green shading indicates more robust prospects for future assessments while pink shading indicates low confidence due to small sample count.

Arsenic and Copper

Arsenic and copper show concentrations in breccia uranium pipe deposits comparable to their respective economic grades in primary deposits. Breccia uranium pipe deposits throughout the Colorado Plateau (e.g., [Hack](#), [Pigeon](#), and [Orphan Lode](#) mines) commonly host arsenic and copper typically as accessory sulfide minerals. Historically, milling of uranium ore from these deposits took place at [23 regional facilities](#) licensed by the Atomic Energy Commission rather than at individual mine sites. These mills, now decommissioned, have each gone through some degree of remediation which likely obscures the tailings grade and complicates recovery. Tailings from the sole operating uranium mill today (White Mesa) could contain similar arsenic and copper concentrations since it

sources ore from a breccia pipe uranium mine (Pinyon Plain). White Mesa also processes other ore types, potentially diluting arsenic and copper fractions.

Titanium

Titanium shows grades in high-sulfidation (HS) epithermal silver-gold $\pm$ Cu deposits (e.g., [Goldfield district, Nevada](#); [Summitville, Colorado](#)) comparable to economic grades in heavy mineral sands. Here, titanium originally occurs as refractory rutile and anatase and ends up in flotation tailings or leach residue depending on the milling/processing route.

Zirconium and Hafnium

Zirconium and its coproduct hafnium show grades in bauxite (aluminum ore) comparable to heavy mineral sands, likely occurring in zircons. Historic bauxite mining predominantly occurred across [Arkansas](#), Alabama and Georgia. Bauxite milling produces limited tailings with the majority of material transported off site to alumina refineries (i.e., Atalco plant, Louisiana; Burnside plant, Louisiana). Further investigations should delineate the fractions concentrated in bauxite mine tailings versus alumina refinery residue.

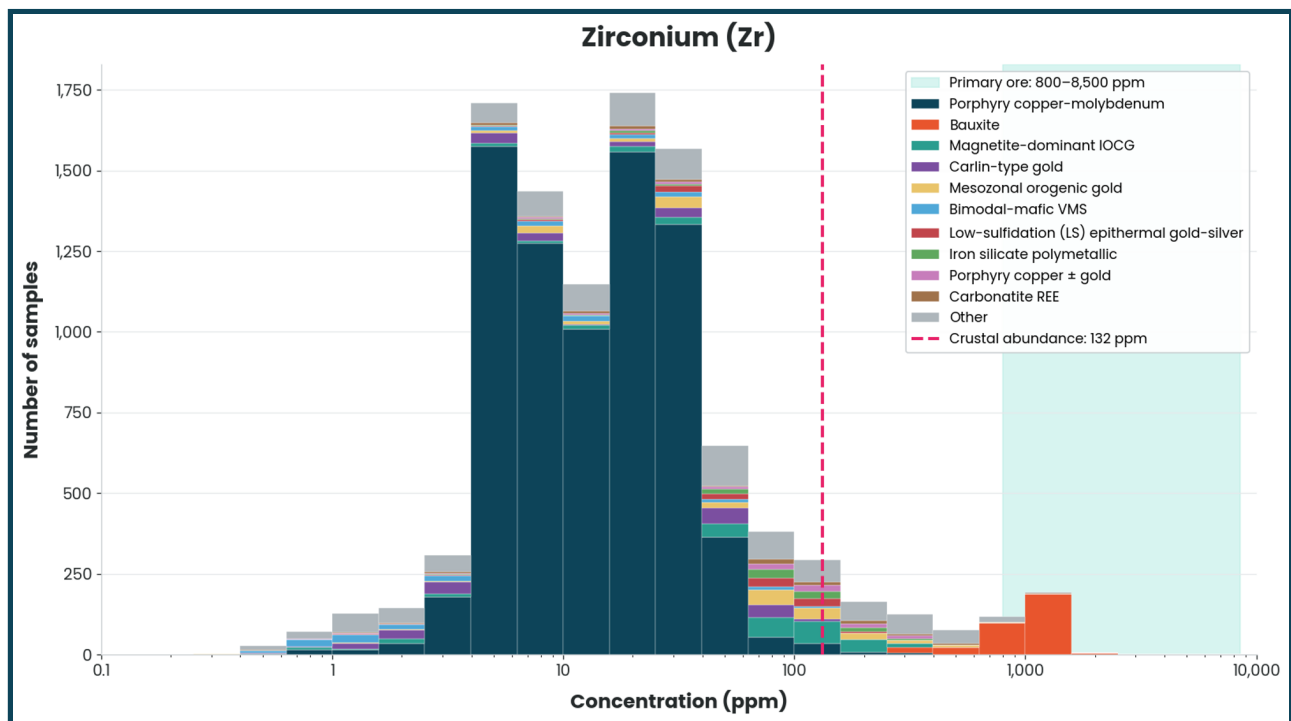


Figure 2: Accessory zirconium and hafnium (hafnium not shown) exhibit concentrations in bauxite deposits comparable to their economic grades in heavy mineral sands, indicating potentially feasible recovery from either bauxite mine tailings or alumina refinery residue.

SUMMARY

This remarkably brief overview of potential mine tailings prospects from a sample database of 29,000 samples, assembled by the combined efforts of the Critical Minerals Mapping Initiative, Geoscience Australia, the Geological Survey of Canada, and the United States Geological Survey, emphasizes that critical minerals recovery potential from mine tailings waste is highly limited and

highly mineral-specific. Policymakers should not misinterpret mine tailings as a large-scale solution for U.S. critical minerals security.

Histograms for each element are presented in the appendix, with detailed data in the Supplementary Information.

METHODS AND DISCUSSION

Methodological Approach

We generated grade distributions from rock sample data within the [Critical Minerals in Ores](#) database hosted by Geoscience Australia. This database provides geochemical compositions of over 29,000 samples from hundreds of active and historic mines globally, representing dozens of deposit types.

Results throughout this study exclude samples coded as mineral concentrates, negative values caused by samples below detection limits, samples from deposits with little relevance to current or historical U.S. production (e.g., ionic adsorption clays), and samples from deposit types with low coverage (arbitrarily $n < 10$). Importantly, the database does not include coal deposits or industrial process waste, and did not allow assessment of fluorspar, graphite, potash, or silicon.

Grade distributions represent material that mines would reasonably consider ore. To approximate this, we excluded samples that did not pass a representative cut off criteria assigned to each deposit type.

Polymetallic deposits received a cut off value (USD/metric ton) representative of unit operating cost for that deposit type (mining + milling + administration). Samples qualified based on the sum product of eligible elements assuming 50 year inflation-adjusted average metal prices, and nominal recovery and payability rates (disregarding treatment, royalty and penalty charges).

In alignment with a [similar study](#), all other deposit types received a cut off grade based on a single element that likely dictates mining decisions (i.e., gold in Carlin-type deposits). In these cases, cut off grades assumed a concentration of 20x that element's crustal abundance (or 10x in the case of iron, since a 20x factor would result in concentrations exceeding pure iron). We used reported cut off grades for aluminum in bauxite and phosphorus in phosphorite deposits since these constitute the only 2 cases assigned to those elements.

Grade distributions apply a nominal dilution factor of 10% to account for the inevitable mixing of waste rock during mining operations. Dilution can range much higher at specific mines. The full dataset and summary metadata including specific cut off criteria are available in the Supplementary Information.

Elements in Tailings that Mines Target as Products

Prospects for recovering an element from the tailings of a mine that originally targeted the same element for production (e.g., gold in the tailings of a Carlin type gold mine) require a different

assessment approach. Grade distributions in these cases show high concentrations equal to the element's primary ore grade, but tailings concentrations will be much lower for two reasons.

First, our cut off methodology filters the dataset to samples that mines could reasonably consider ore based on sample grades of the element(s) a mine targets for that deposit type. In practice, mines model these samples into 3 dimensional blocks with lower average grades which we cannot estimate without spatial data. So distributions for these elements suggest a higher average grade than what would actually go to the mill, exhibiting exaggerated high grade tails and higher central tendencies.

For example, silver samples from high sulfidation epithermal deposits show a median grade of ~110 ppm. However, the [La Coipa](#), [Martabe](#), and [Pueblo Viejo](#) mines report mill head grades of roughly 60, 25, and 20 ppm, respectively.

Second, distributions do not account for the recovery of products at the mill, which further reduces the tailings concentrations. For instance, the [Middle Tennessee](#) mine reports a zinc mill head grade of 32,000 ppm and a recovery rate of 94% which indicates a zinc tailings concentration of roughly 2,000 ppm—far lower than the median grade of ~124,000 ppm exhibited in the zinc distribution for that deposit type (Mississippi Valley) and well below zinc's economic range for primary ores.

Critical mineral policy should not rely on recovering the remaining amounts of targeted elements from the tailings of modern mines. Those amounts represent the limits of what current processing techniques can feasibly recover. Developing better novel techniques is a worthwhile area of research, but mineral security must pursue readily available measures while additional recovery from tailings remains hypothetical.

Even if a new processing technology allows additional recovery from tailings, it will also enable mining of new mineral deposits that would likely prove more economically feasible with higher production volumes. Industry has already demonstrated this effect during reprocessing of historic tailings that predated current recovery methods, or when targeting exceptionally high grade deposits that have since depleted.

Magnetic separation, for example, helped the U.S. iron industry develop new mines from low grade taconite deposits in addition to recovering additional iron from historic high grade tailings. But at its peak in [2015](#), reprocessing of tailings contributed only [5%](#) of U.S. iron production and only proved feasible under exceptionally high iron prices.

Starting in the 1920s, industry began reprocessing historic zinc tailings generated before the advent of flotation. To operate feasibly, however, reprocessing relied on integration with new mines that targeted the same newly accessible low grade, disseminated ore. Ultimately, tailings contributed only 10% of U.S. zinc production at its peak in [1936](#) before depleting in the 1950s.

Indeed, reprocessing of historic tailings for the targeted commodities has occurred only periodically and at best merely supplemented mineral production from conventional mining. So critical mineral policy must treat the possibility of new processing technologies as part of a comprehensive approach to sourcing mineral supplies rather than as an alternative to new mines.

Policymakers also should not rely on critical minerals production from historic tailings. Some opportunities surely exist, as the U.S. possesses many abandoned mines which federal mapping and characterization efforts will continue to evaluate. However, industry has already picked over many historic sites over the last century, leaving fewer and likely smaller prospects that may need to rely on new co-located mining operations, as in the past.

Subgrade Material

We additionally analyzed accessory element concentrations of samples that did not qualify as ore, identifying 11 cases of competitive enrichment. This analysis captures prospects in waste material that mines may have either mixed with ore material en route to the mill or excavated separately during construction of tunnels and shafts. Note that such separately excavated waste rock loses the economic advantage of prior crushing at the mill.

Element	Deposit Type	n	Median Grade (ppm)	Economic Grade (ppm)
Titanium	Peralkaline igneous high field strength	30	8,030	5,000
Titanium	Replacement zinc-lead	8	6,650	5,000
Arsenic	Epizonal orogenic antimony ± gold	5	7,570	2,000
Nickel	Collapse breccia pipe uranium	4	11,036	6,600
Cobalt	Collapse breccia pipe uranium	4	3,448	1,900
Arsenic	Collapse breccia pipe uranium	4	11,000	2,000
Arsenic	Porphyry tin	3	2,040	2,000
Copper	Porphyry tin	3	2,150	1,500
Indium	Porphyry tin	3	82	60
Arsenic	Greisen tungsten-molybdenum ± Bi	1	4,730	2,000
Yttrium	Greisen tungsten-molybdenum ± Bi	1	278	250

Table 2. Accessory elements that show enrichment in the waste rock of mineral deposits. Mines inevitably incorporate some amount of waste to excavated ore which can end up in tailings or waste rock piles.

We note the low sample counts across all 11 cases. Each case requires further investigation to delineate the specific mode of occurrence and correlation with the target commodity. For example, these samples may represent margins of a mineral deposit with no relation to the actual ore body, making it less likely that historic mine sites actually excavated such materials.

APPENDIX: ELEMENT CONCENTRATION DISTRIBUTIONS BY DEPOSIT TYPE

Histograms represent the range of concentrations from samples that mines would likely consider ore and send to the mill. The median concentration for each deposit type roughly approximates the bulk composition of mine tailings. Medians that lie in the shaded region represent promising prospects for tailings recovery because the elements occur at concentrations comparable to their grade in primary ores and therefore have proven economically feasible to recover. The high grade tails of each distribution do not realistically represent the concentration in tailings because the mining and milling process blends high grade ore with low grade ore and waste rock. Medians near the dotted line are similar to that element's crustal abundance concentration which means the tailings are no more enriched in that element than ordinary rock or sediment, making recovery effectively impossible. Detailed data specifying each median value including subgrade material not presented below are available in the Supplementary Data file.

These distributions do not accurately represent the tailings concentration for elements in deposits types where that element is the targeted commodity because mills recover that element. The aluminum histogram below, for example, shows aluminum concentrations from bauxite deposits that are comparable to its economic grade in primary ores specifically because bauxite is an aluminum ore. We present separate histograms for the major base and precious metals by target and nontarget deposit types for better legibility since these elements are routinely recovered from many types of deposits.

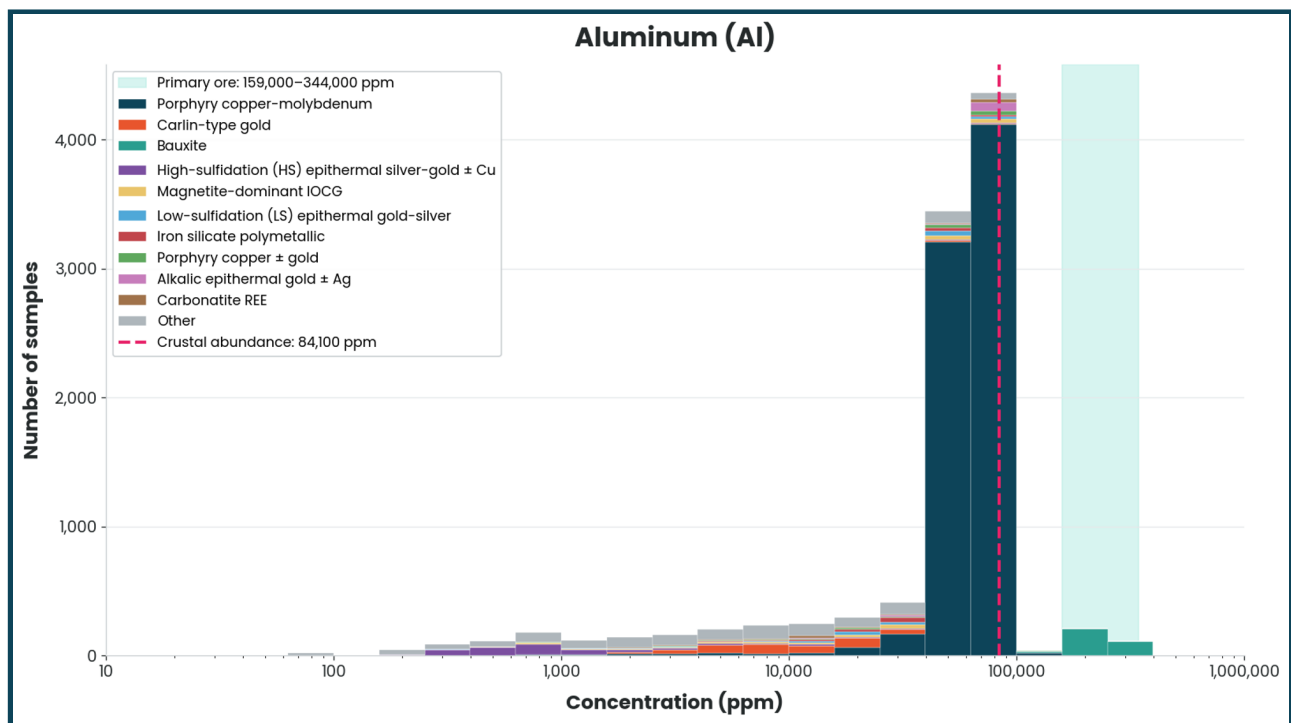


Figure A-1: Policymakers should not expect to source aluminum from mine tailings. Bauxite deposits show elevated aluminum concentrations. However, bauxite mines target aluminum and remove it during the milling process.

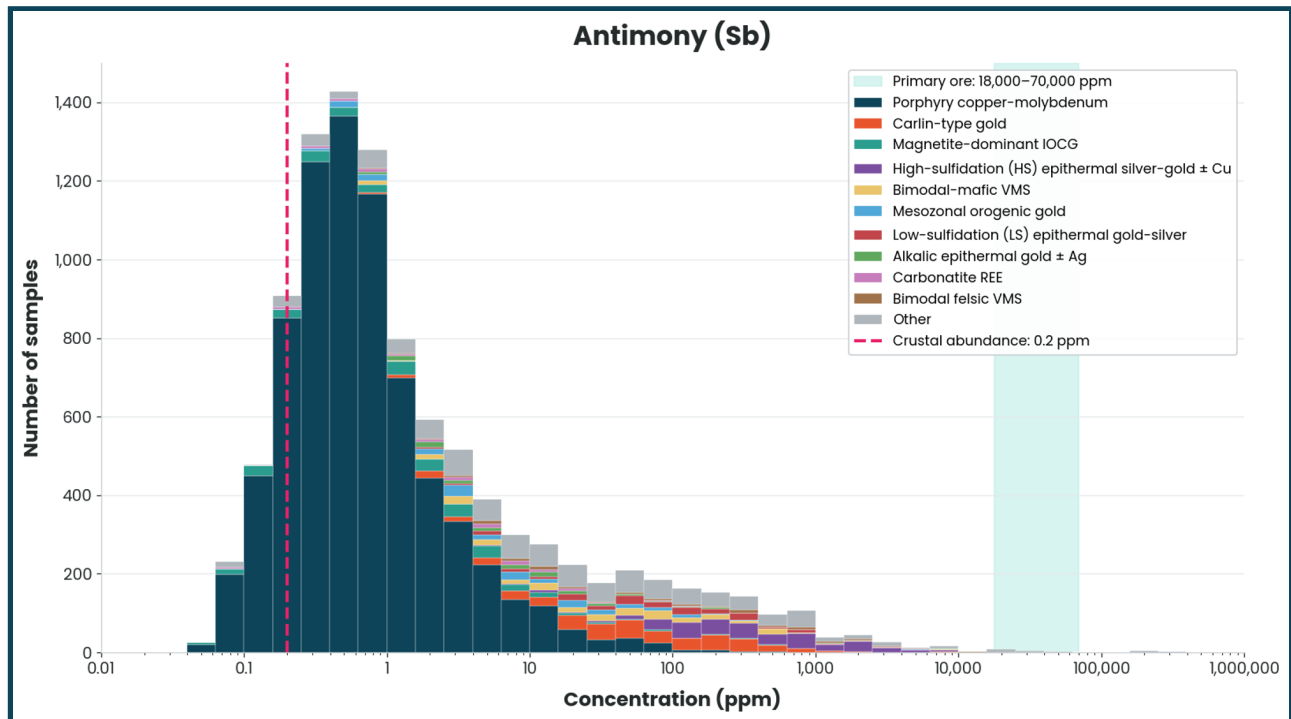


Figure A-2: Policymakers should not expect to source antimony from mine tailings. Rather, policy initiatives should facilitate the recovery of antimony from secondary lead smelting waste which offers proven extraction routes.

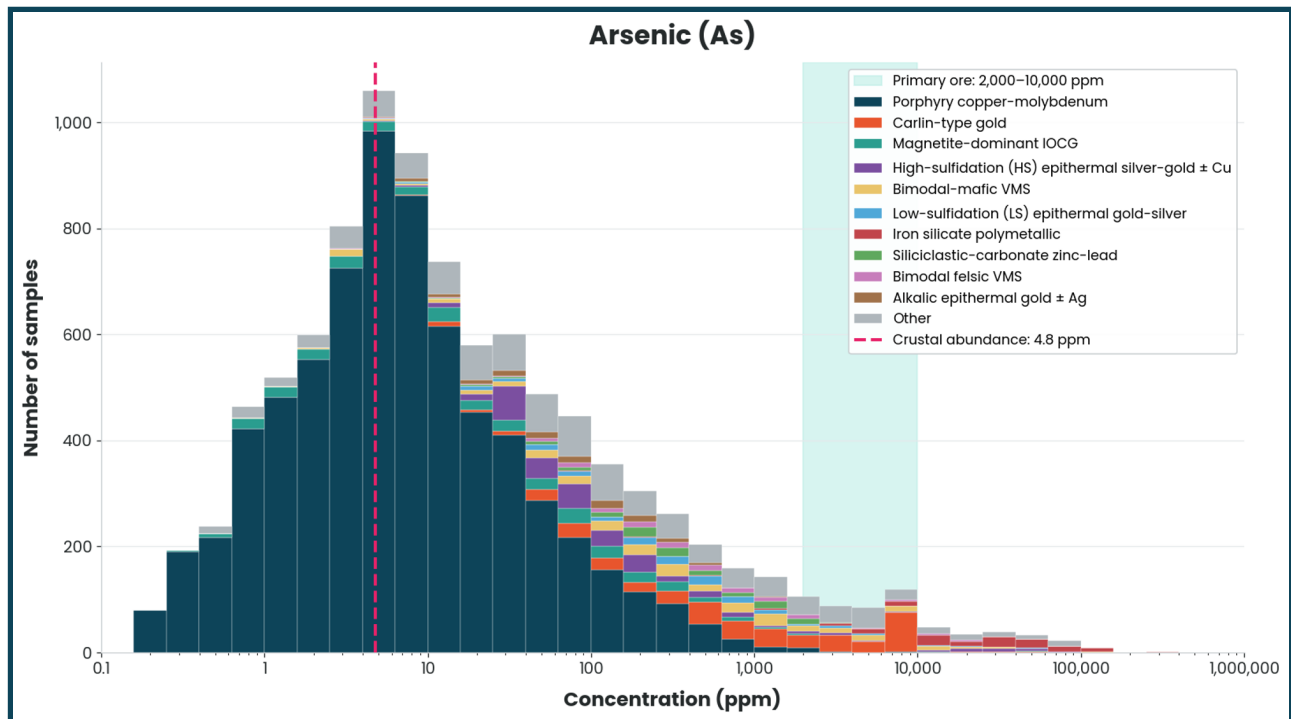


Figure A-3: Opportunities may exist to recover arsenic from collapse breccia pipe uranium, breccia pipe copper, porphyry tin, and vein tungsten mine tailings (shown above under “Other” due to low sample count). Arsenic shows elevated concentrations in other deposit types due to its widespread presence in accessory sulfide minerals. However, actual arsenic concentrations in tailings for these deposit types will be lower since mills remove much of the arsenic which accumulates in refining or smelting waste.

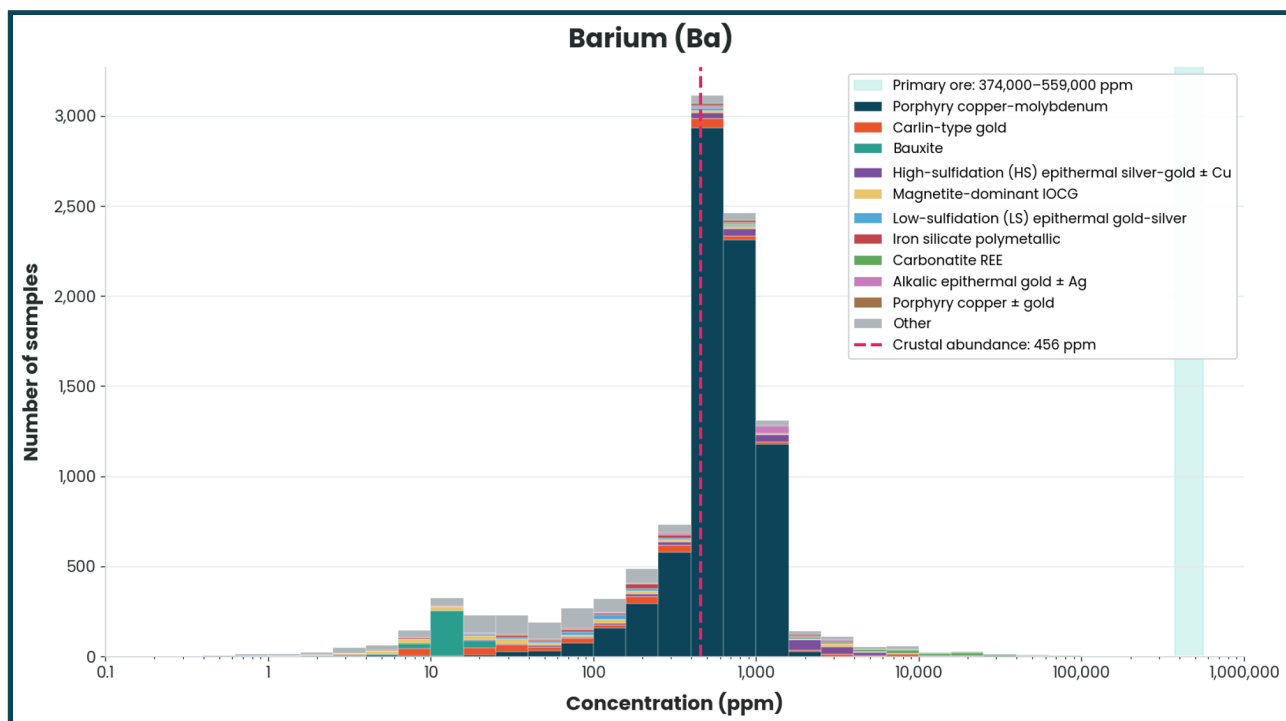


Figure A-4: Policymakers should not expect to source barium (i.e., the critical mineral “barite”) from mine tailings.

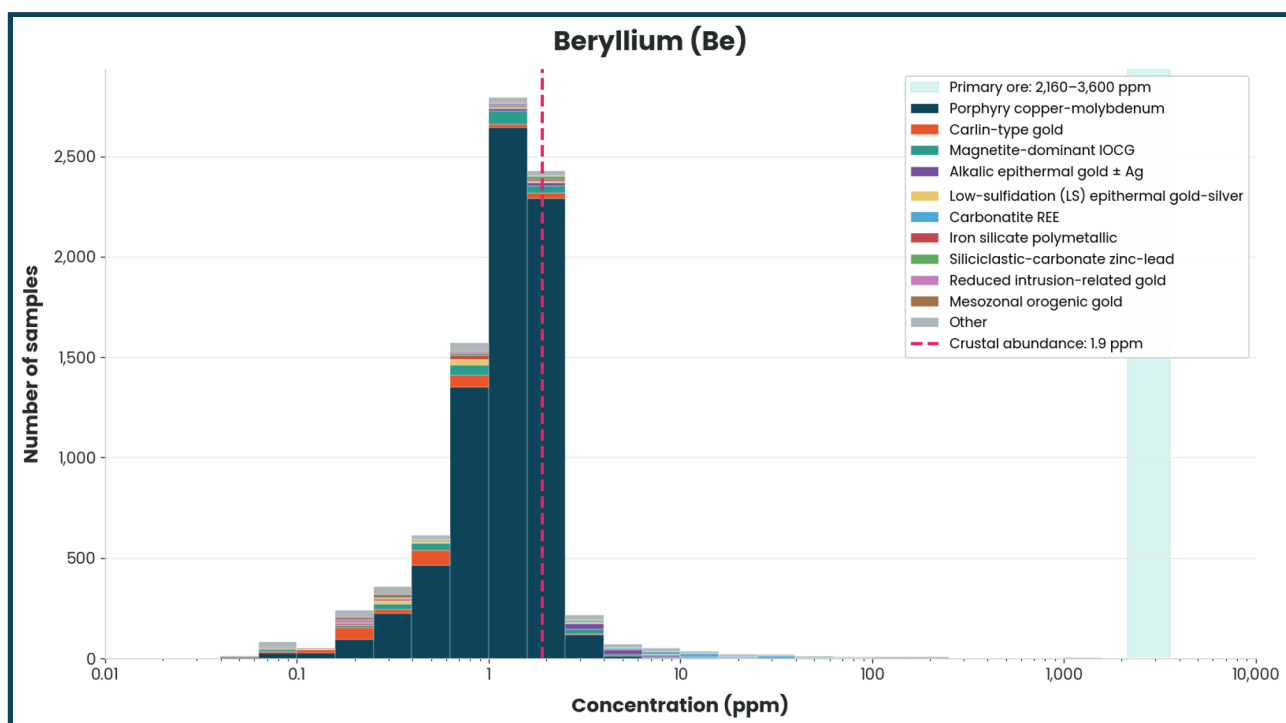


Figure A-5: Policymakers should not expect to source beryllium from mine tailings.

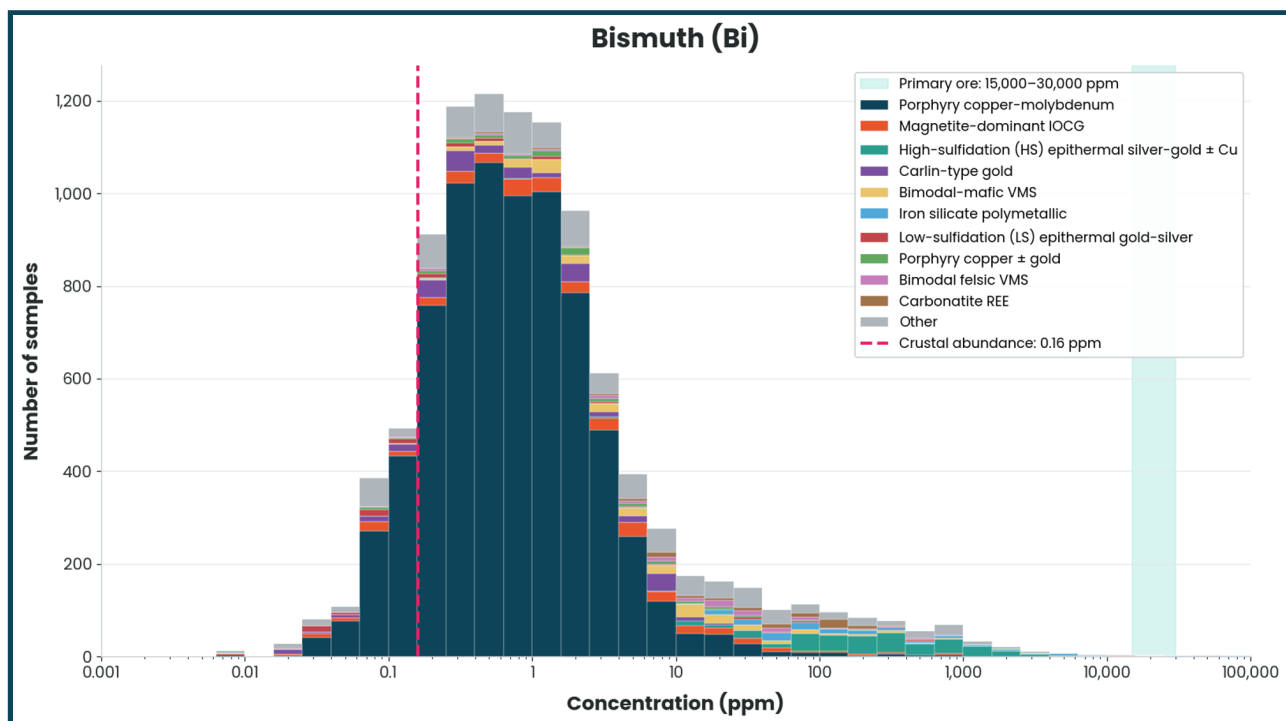


Figure A-6: Policymakers should not expect to source bismuth from mine tailings. Rather, policy initiatives should facilitate the recovery of bismuth from lead and zinc smelting waste which serve as the primary production routes for bismuth and offer proven extraction methods.

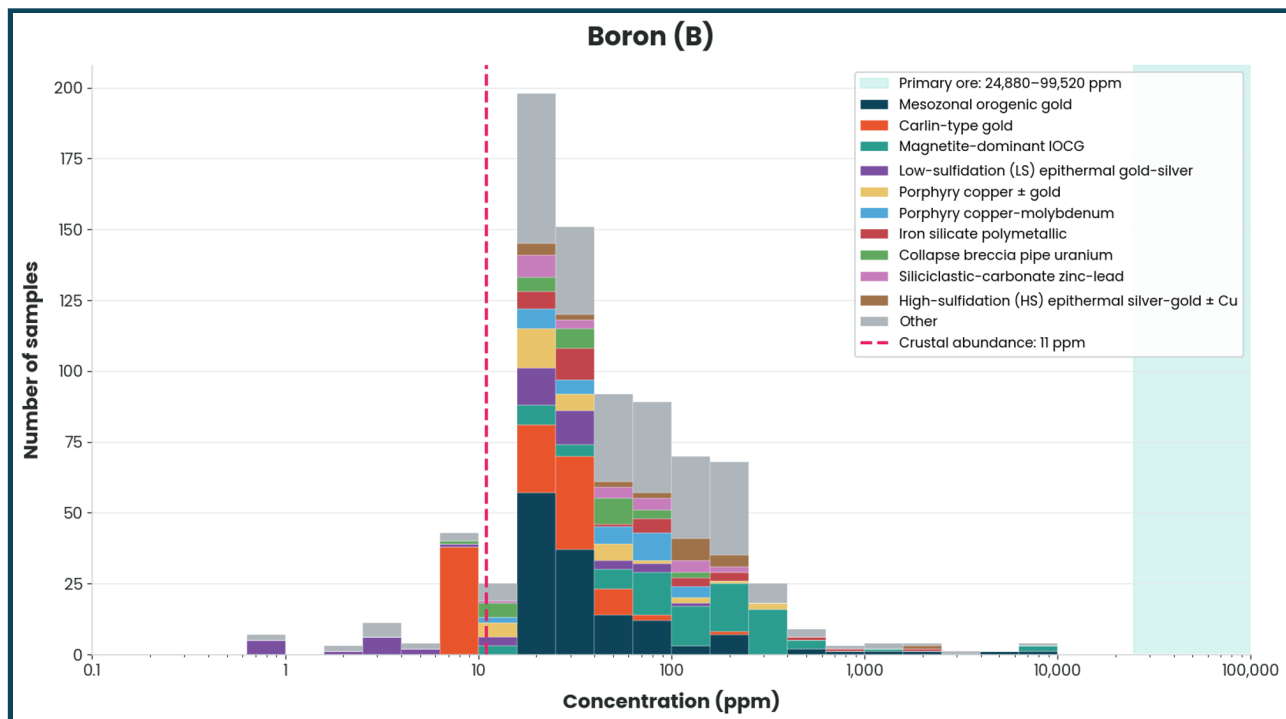


Figure A-7: Policymakers should not expect to source boron from mine tailings.

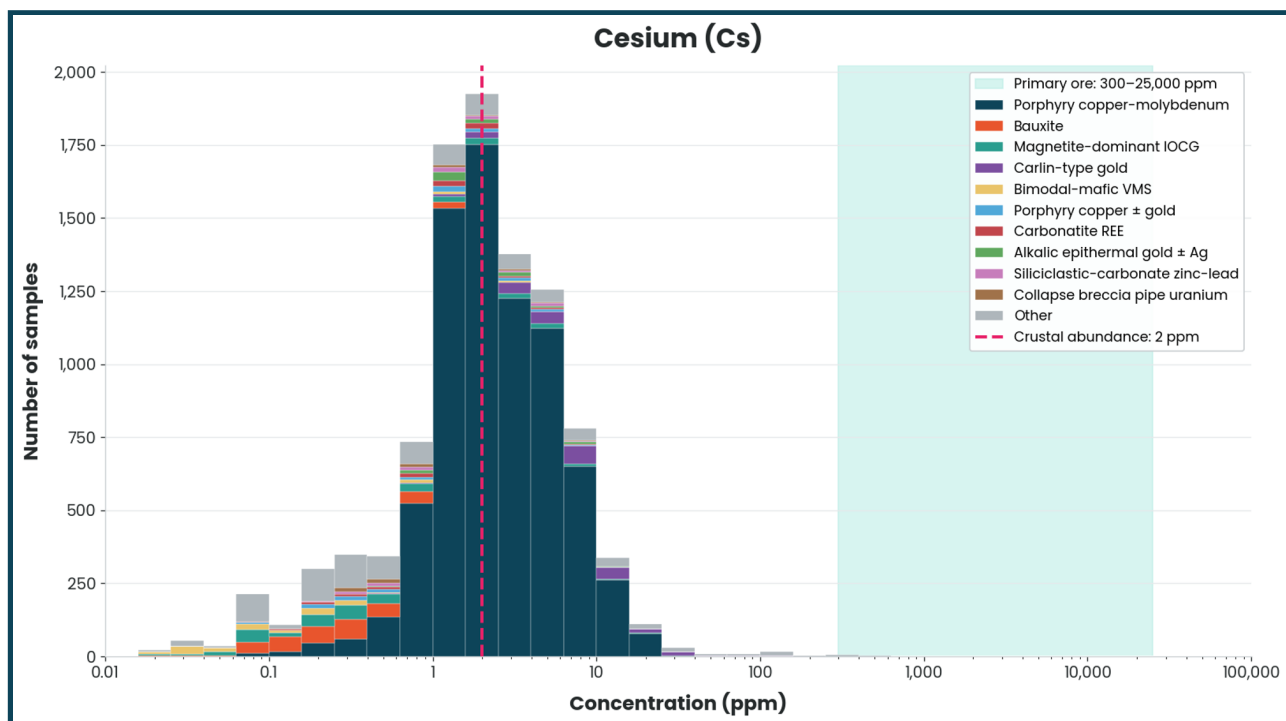


Figure A-8: Policymakers should not expect to source cesium from mine tailings.

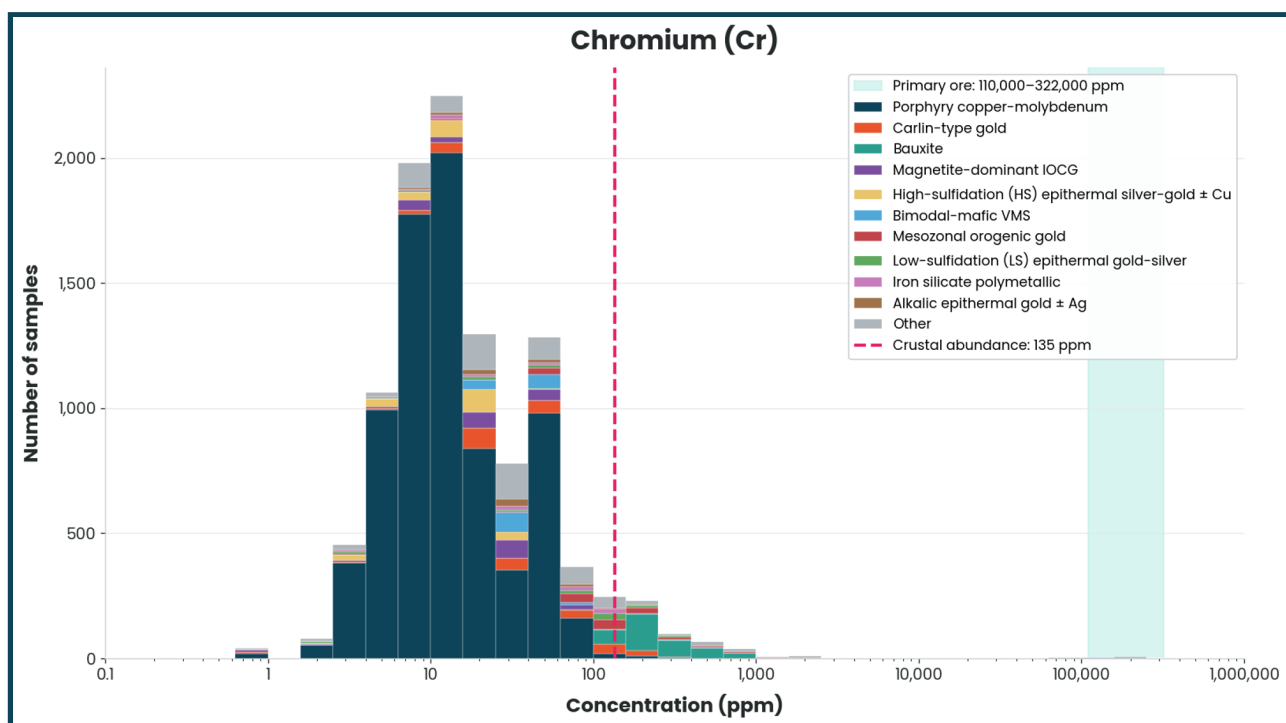


Figure A-9: Policymakers should not expect to source chromium from mine tailings.

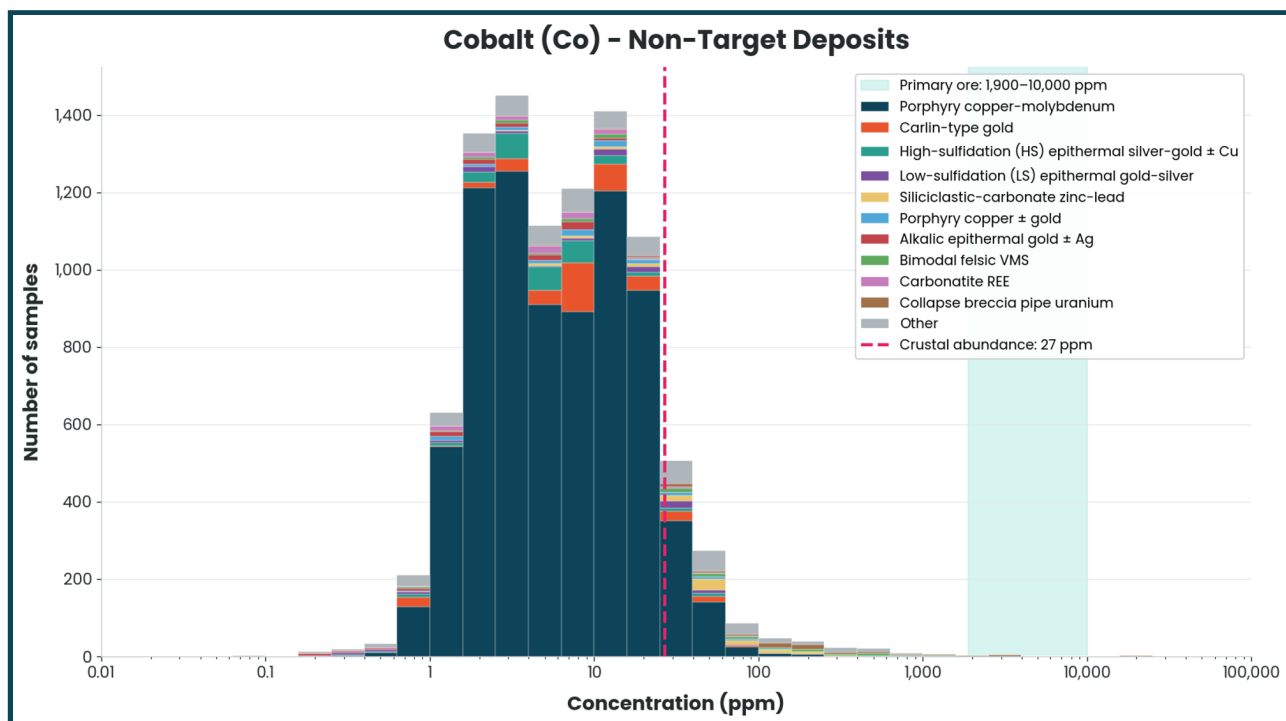


Figure A-10: Policymakers should not expect to source cobalt from mine tailings.

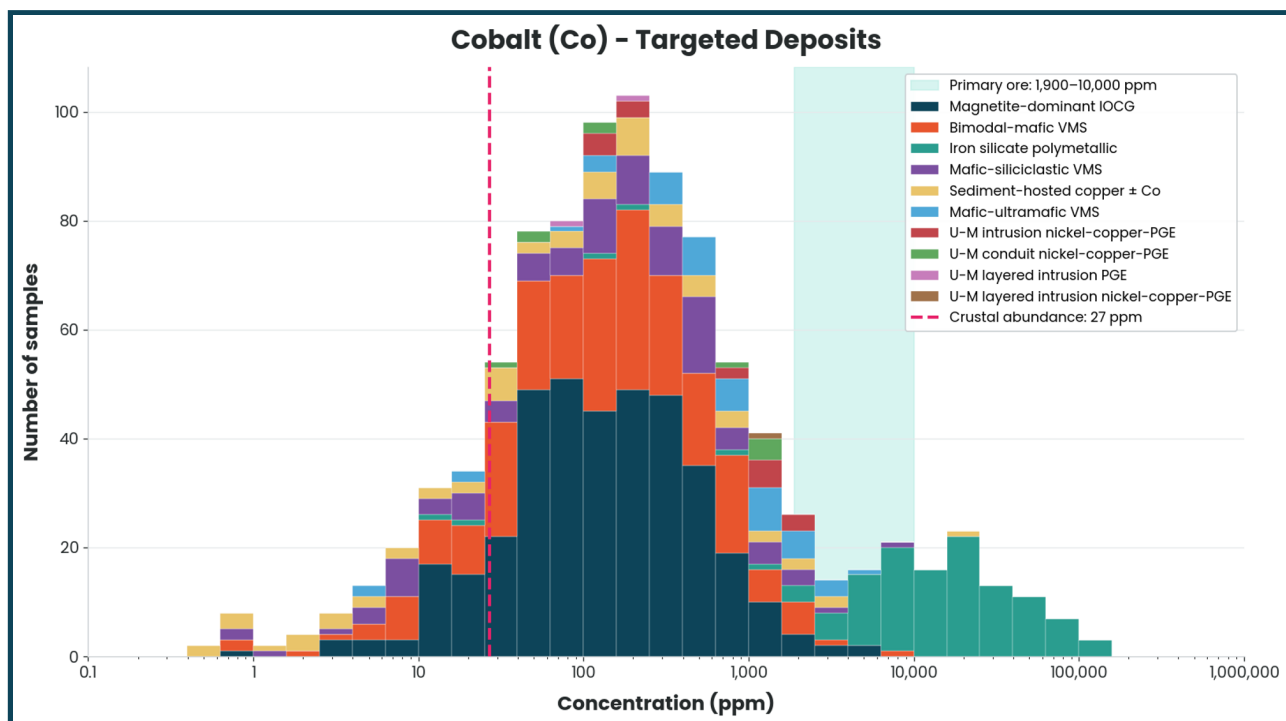


Figure A-11: Cobalt in the tailings of mines that target cobalt in reality will occur at much lower concentrations than those shown above. Policymakers should not rely on recovering additional amounts of cobalt from cobalt mine tailings which remains unlikely and would at best supplement production from new mines.

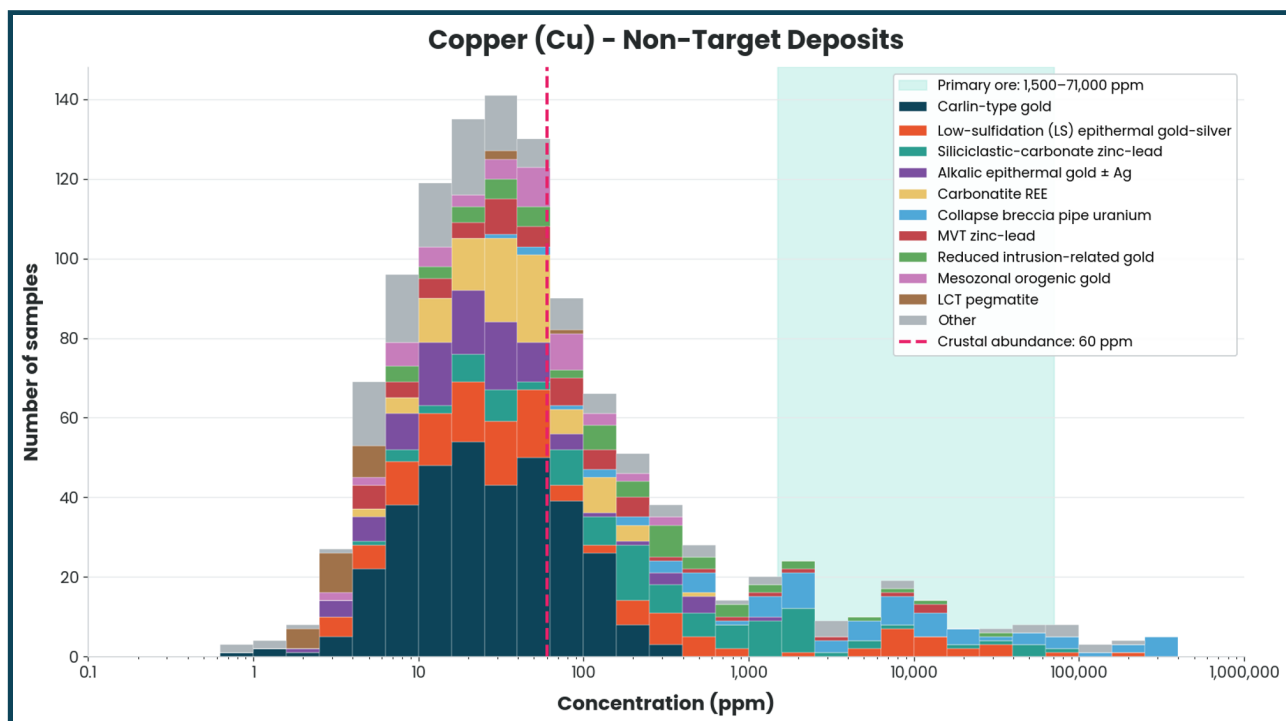


Figure A-12: Opportunities may exist to recover copper from the tailings of collapse breccia pipe uranium, porphyry tin, and vein tungsten mines (porphyry tin and vein tungsten shown above under “Other” due to low sample count).

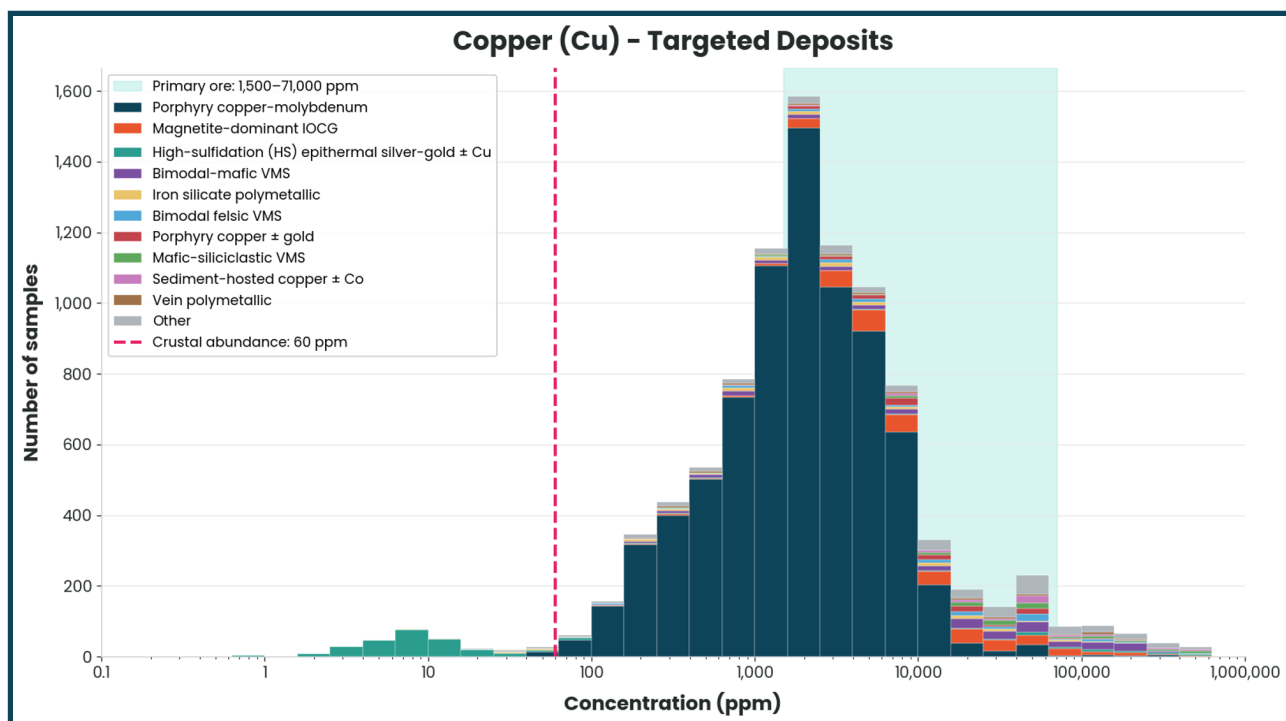


Figure A-13: Copper in the tailings of mines that target copper in reality will occur at much lower concentrations than those shown above since mills recover the copper. Policymakers should not rely on recovering additional amounts of copper from copper mine tailings which remains unlikely and would at best supplement production from new mines.

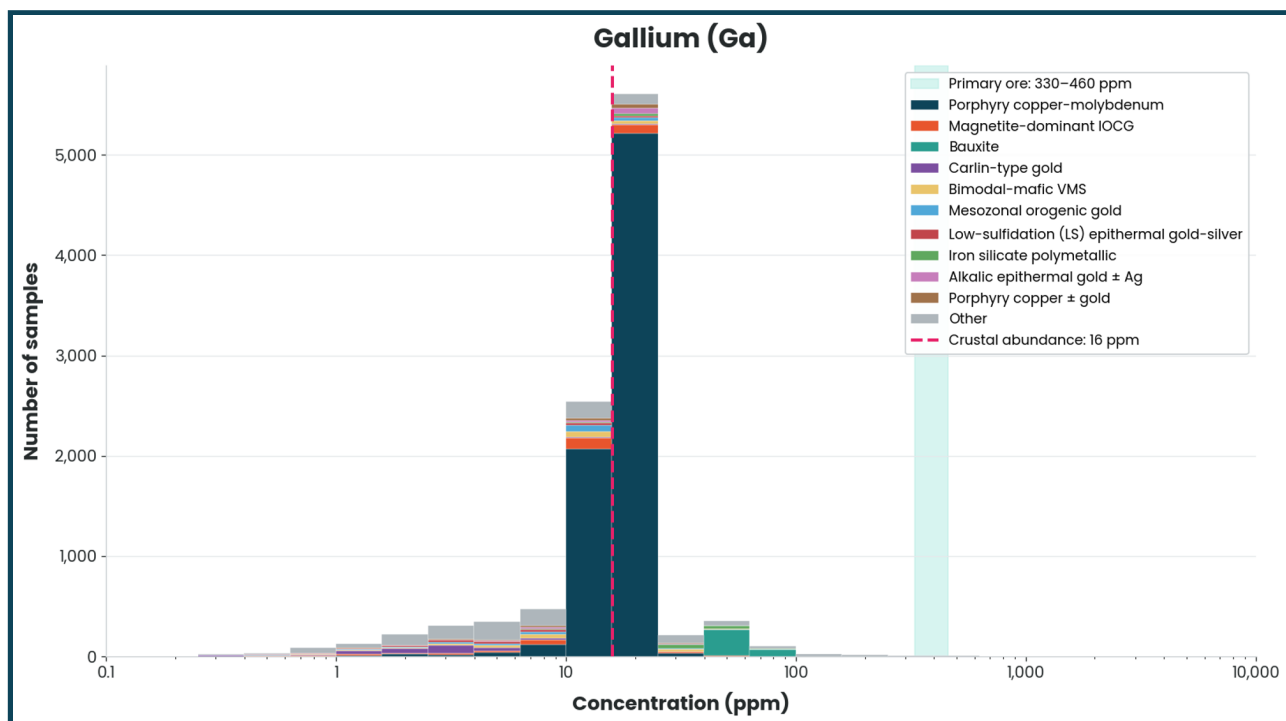


Figure A-14: Policymakers should not expect to source gallium from mine tailings. Rather, policy initiatives should facilitate the recovery of gallium from alumina refinery and zinc smelting waste which serve as the principal production routes for gallium and offer proven extraction methods.

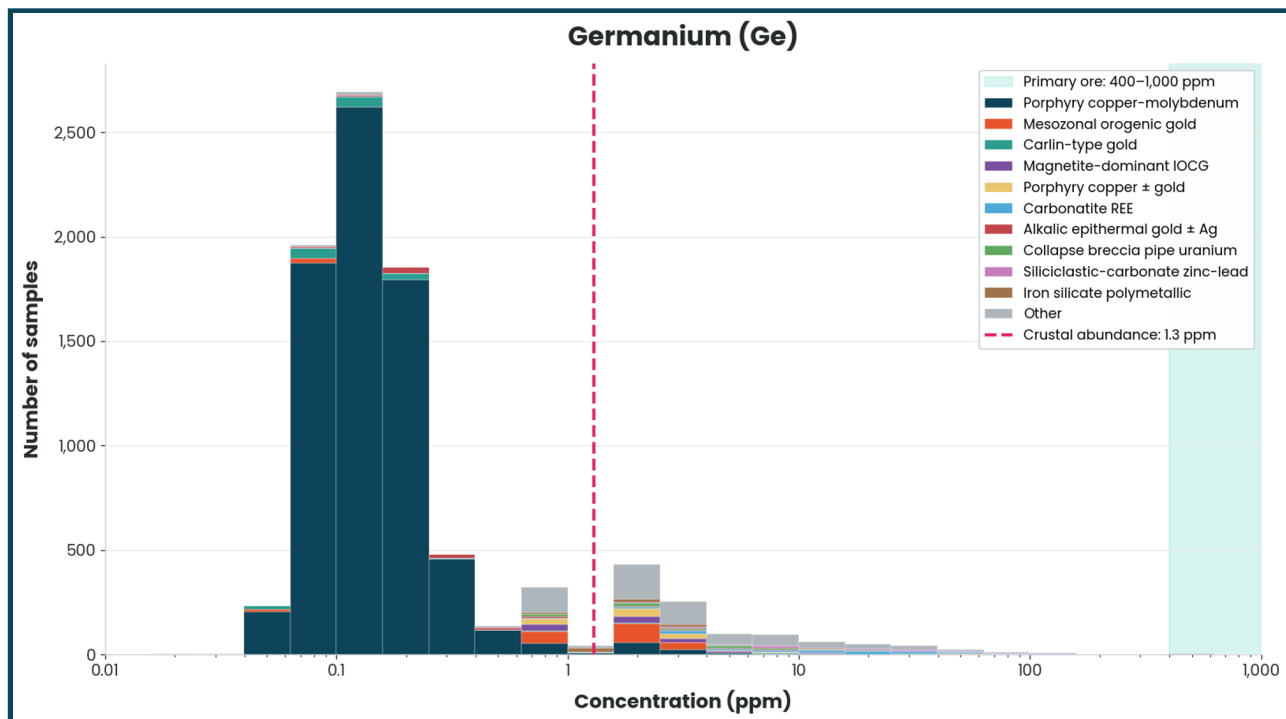


Figure A-15: Policymakers should not expect to source germanium from mine tailings. Rather, policy initiatives should facilitate the recovery of germanium from zinc smelting waste which serves as a principal production route for germanium and offers proven extraction methods.

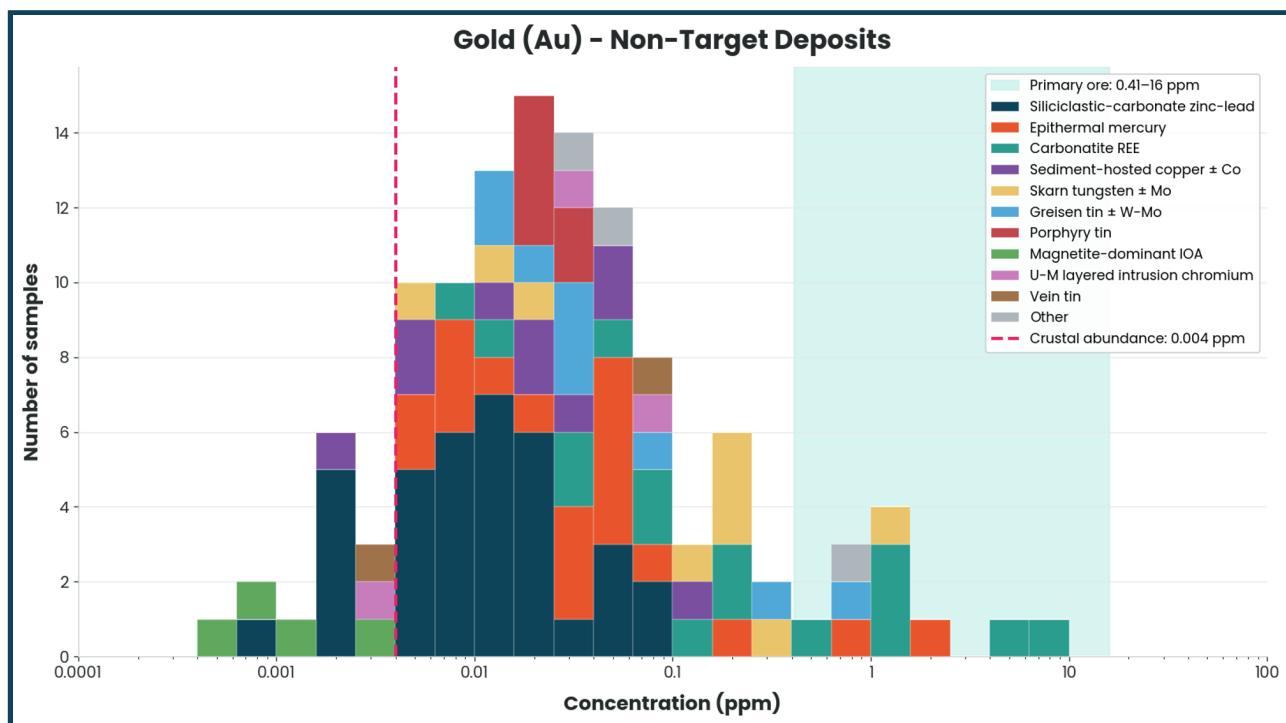


Figure A-16: Policymakers should not expect to source gold from mine tailings.

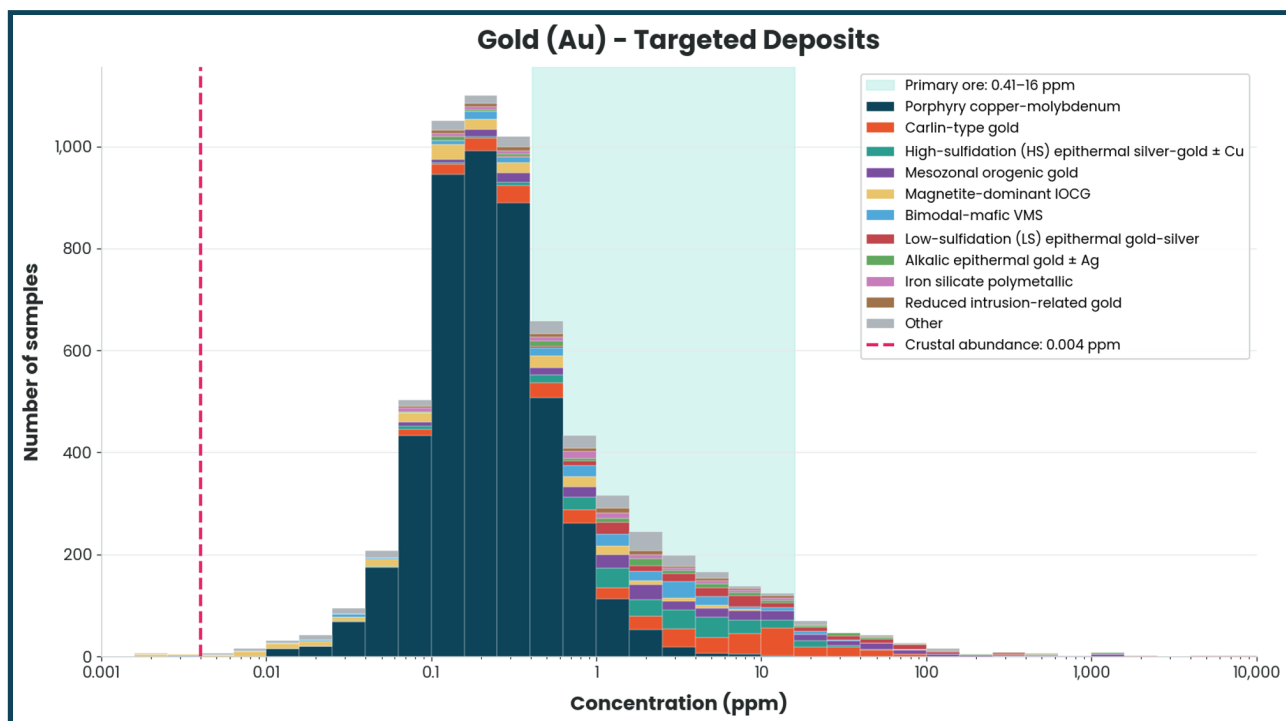


Figure A-17: Gold in the tailings of mines that target gold in reality will occur at much lower concentrations than those shown above since mills recover the gold. Policymakers should not rely on recovering additional amounts of gold from gold mine tailings which remains unlikely and would at best supplement production from new mines.

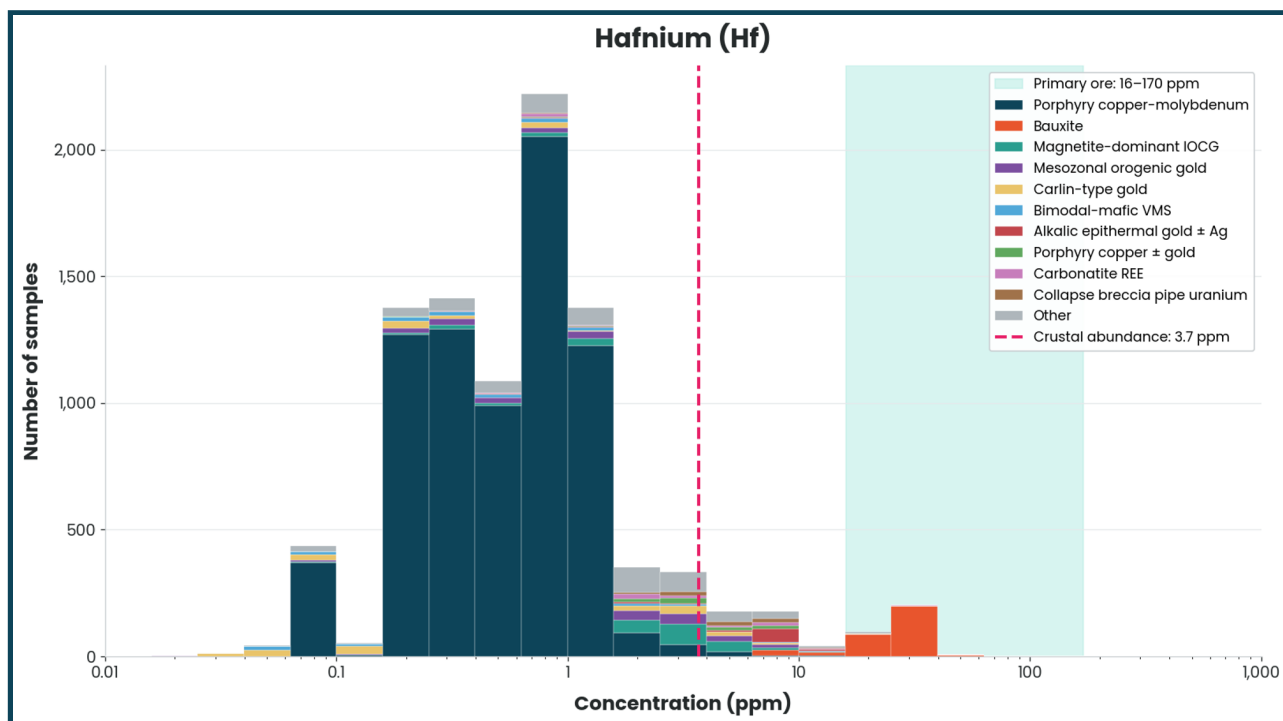


Figure A-18: Opportunities may exist to recover hafnium from bauxite mine tailings or alumina refinery residue.

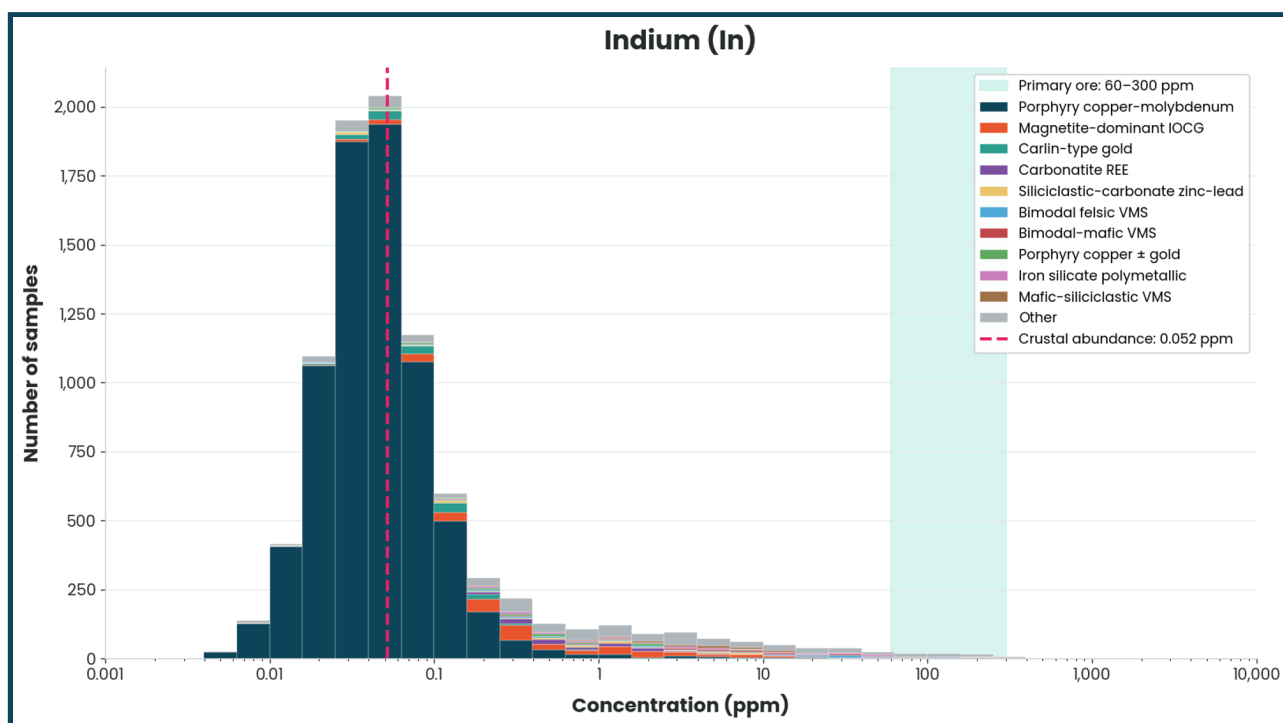


Figure A-19: Policymakers should not expect to source indium from mine tailings. Rather, policy initiatives should facilitate the recovery of indium from zinc smelting waste which serves as the primary production route for indium and offers proven extraction methods. Samples with high indium concentrations come from zinc-bearing deposits where mills would recover the indium along with the zinc.

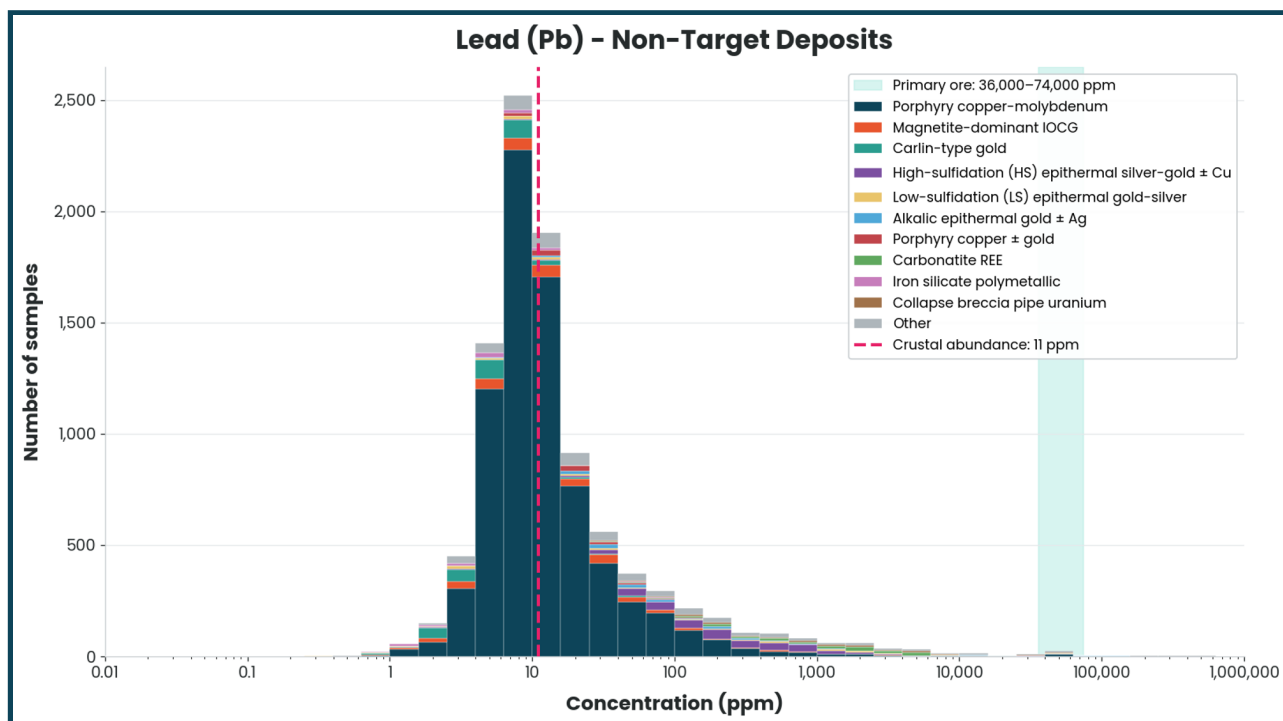


Figure A-20: Policymakers should not expect to source lead from mine tailings.

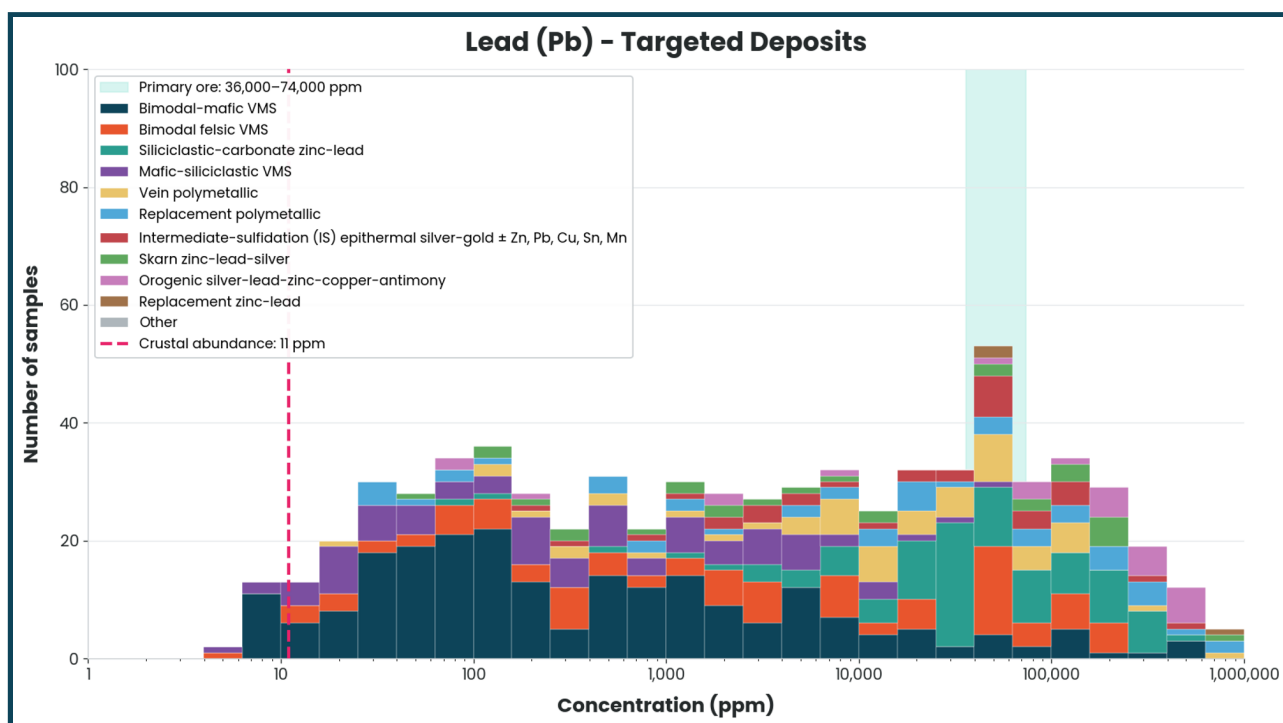


Figure A-21: Lead in the tailings of mines that target lead in reality will occur at much lower concentrations than those shown above since mills recover the lead. Policymakers should not rely on recovering additional amounts of lead from lead mine tailings which remains unlikely and would at best supplement production from new mines.

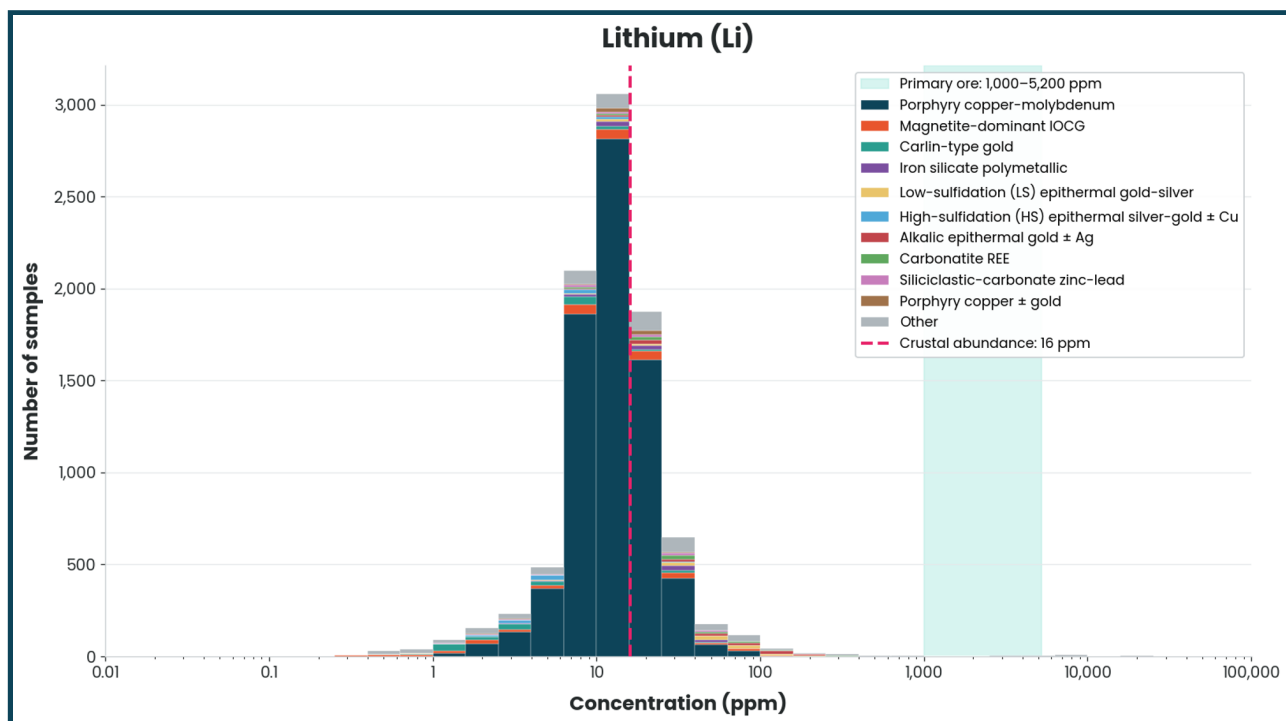


Figure A-22: Policymakers should not expect to source lithium from mine tailings.

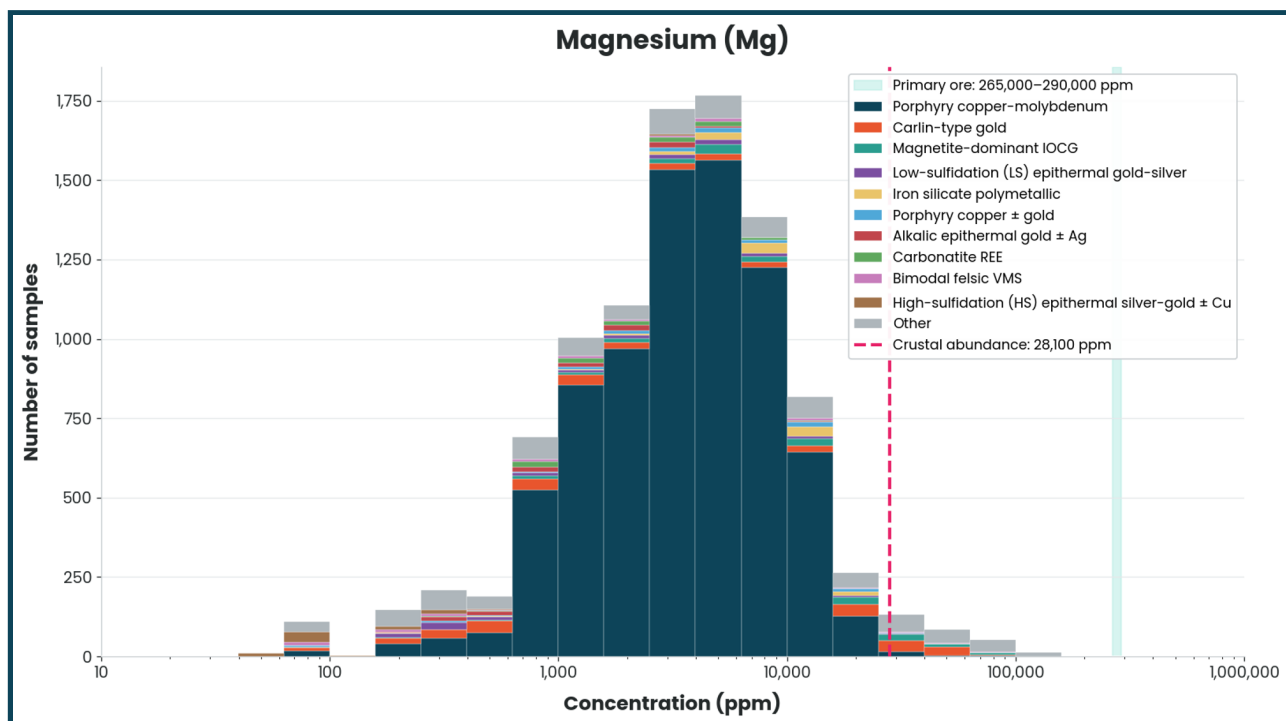


Figure A-23: Policymakers should not expect to source magnesium from mine tailings.

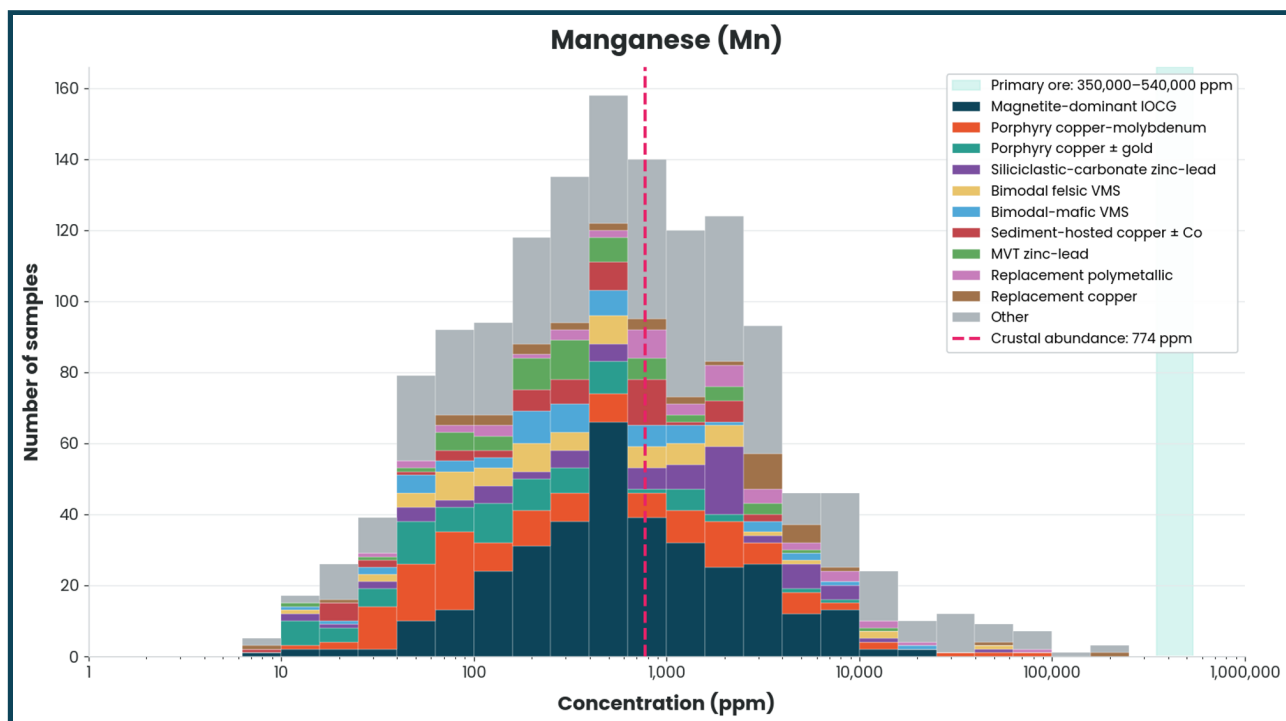


Figure A-24: Policymakers should not expect to source manganese from mine tailings.

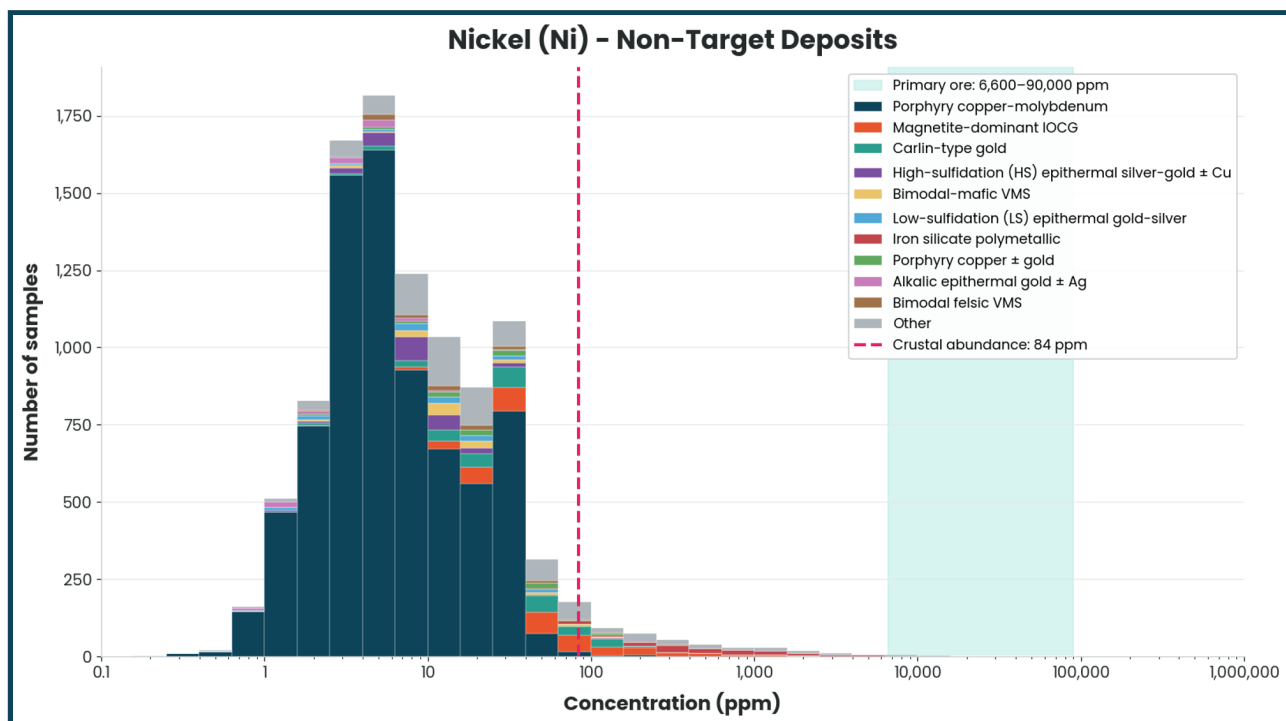


Figure A-25: Policymakers should not expect to source nickel from mine tailings.

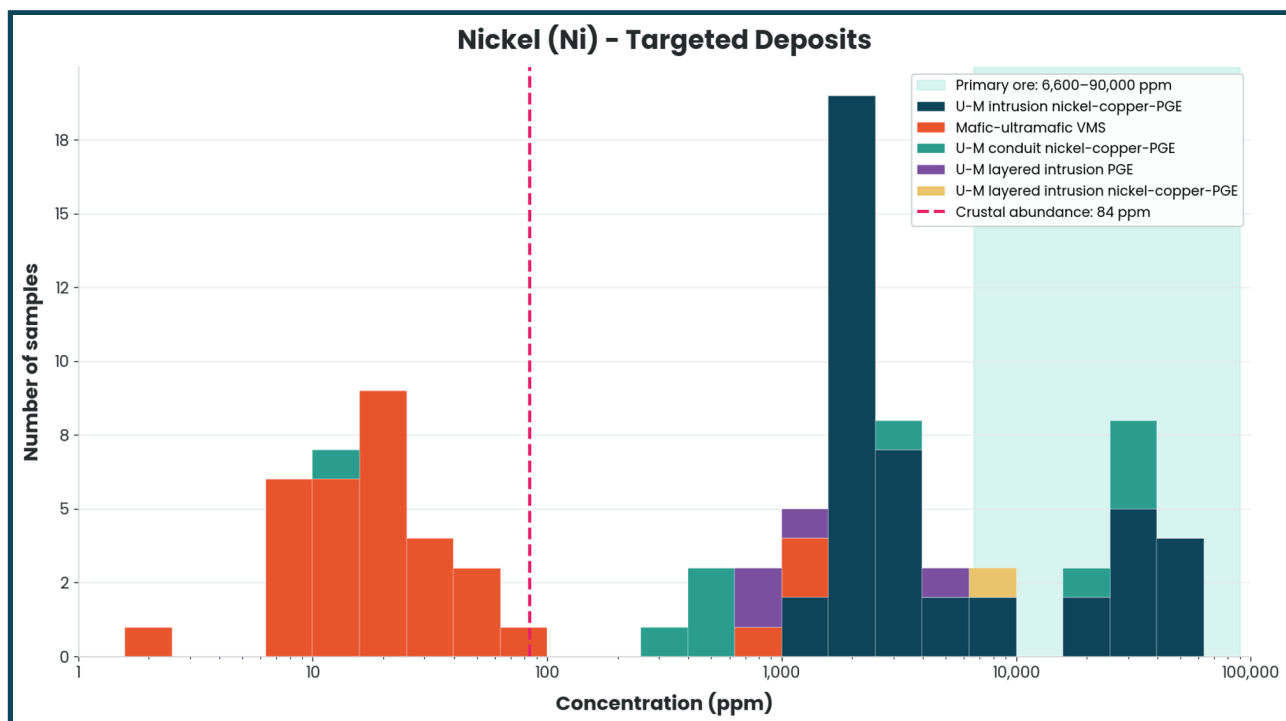


Figure A-26: Nickel in the tailings of mines that target nickel in reality will occur at much lower concentrations than those shown above since mills recover the nickel. Policymakers should not rely on recovering additional amounts of nickel from nickel mine tailings which remains unlikely and would at best supplement production from new mines.

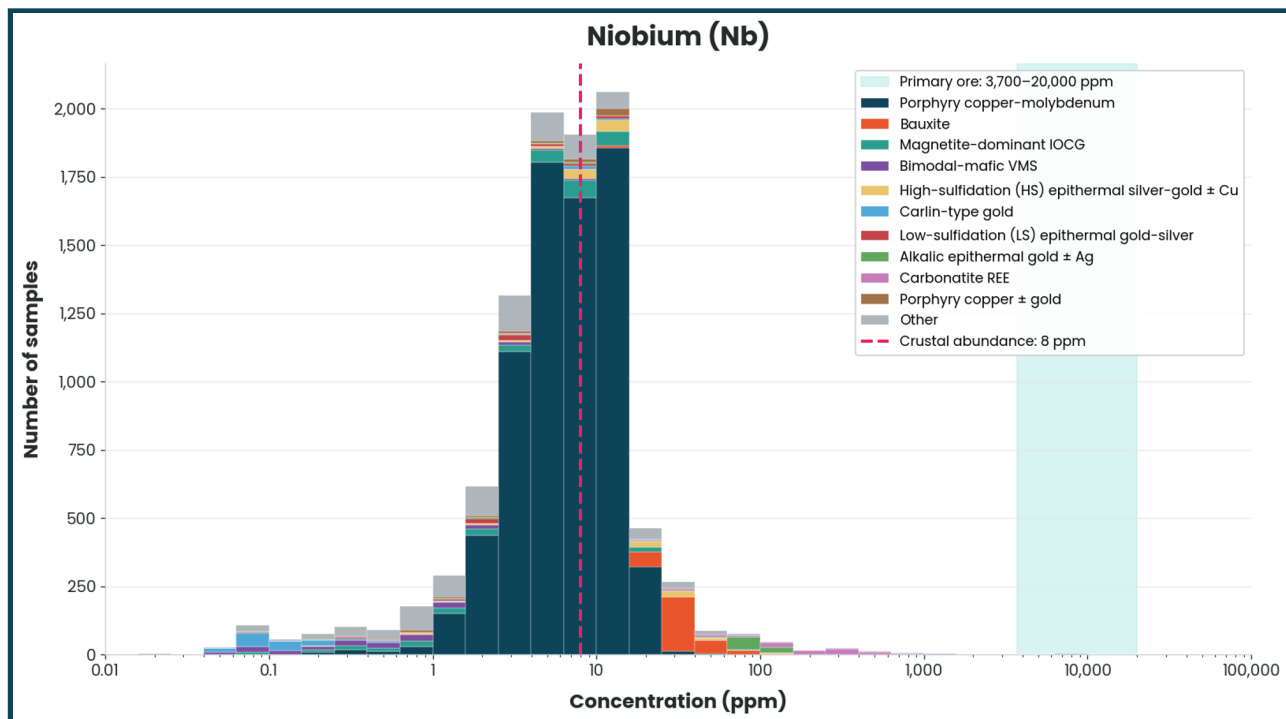


Figure A-27: Policymakers should not expect to source niobium from mine tailings.

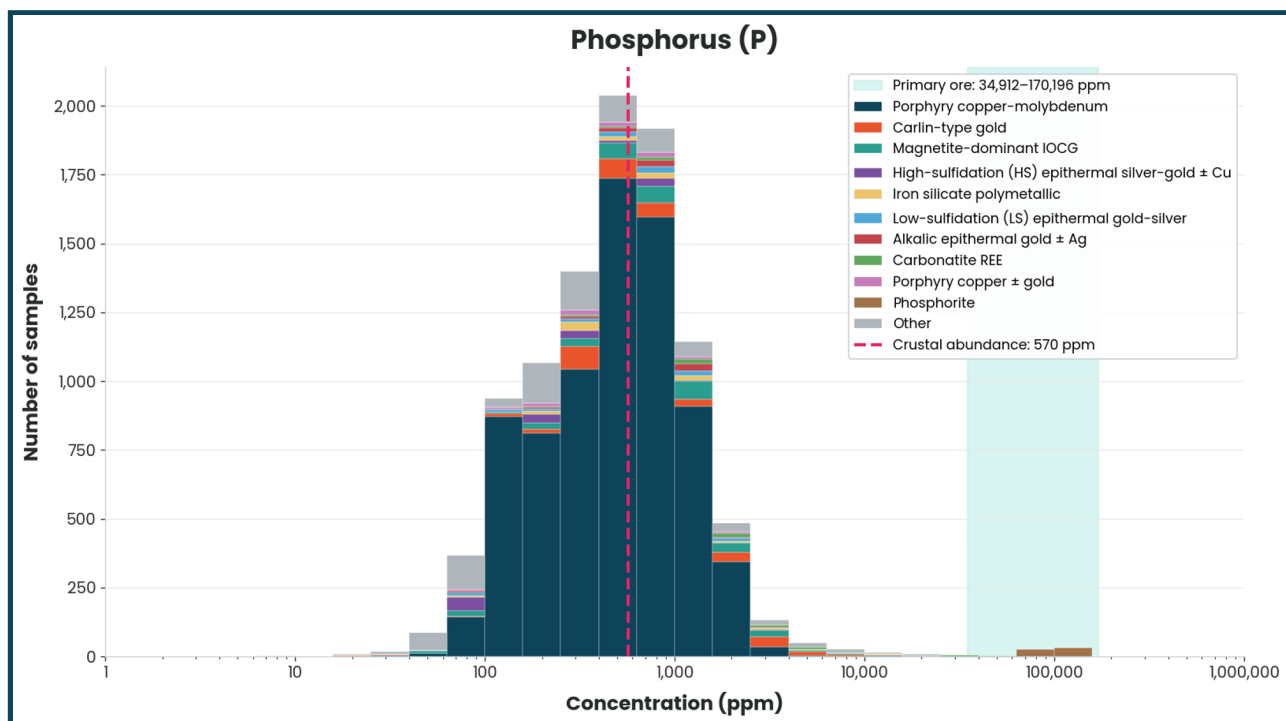


Figure A-28: Policymakers should not expect to source phosphorus (i.e., the critical mineral “phosphate rock”) from mine tailings. Phosphorite deposits show elevated phosphorous concentrations. However, phosphorite is a phosphorus ore so mills would recover the phosphorus at the mine site.

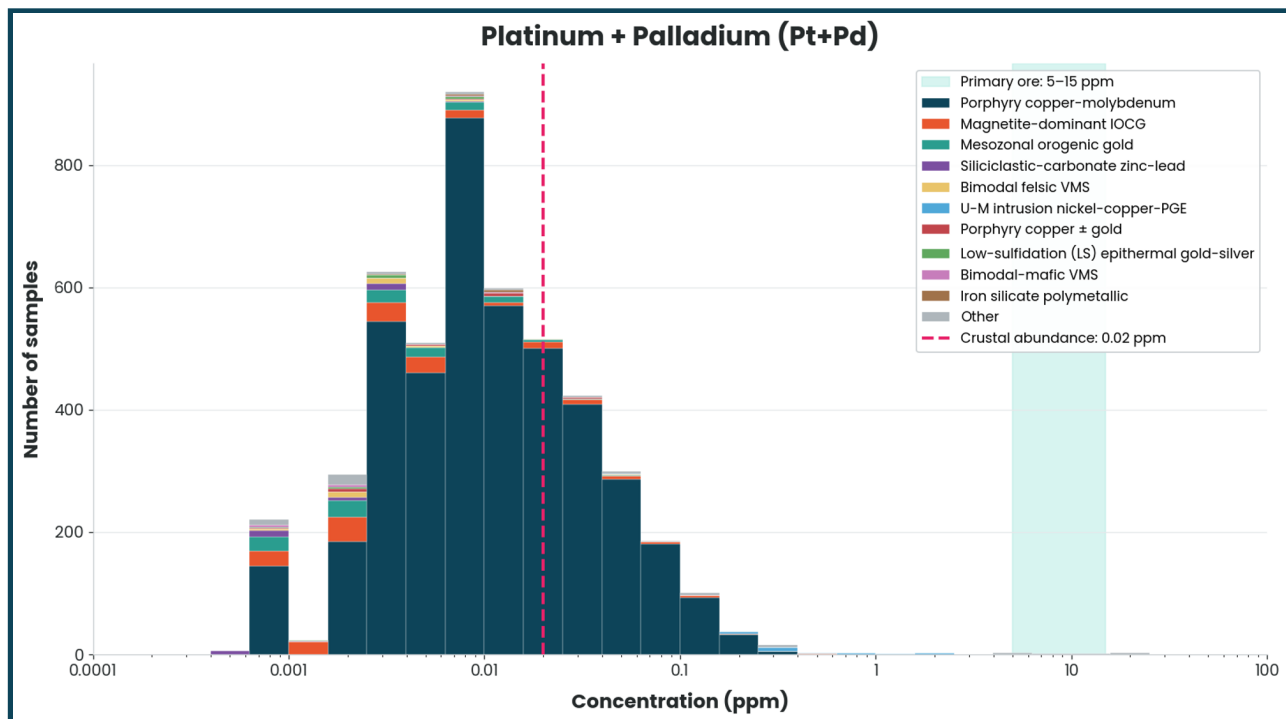


Figure A-29: Policymakers should not expect to source platinum group elements from mine tailings.

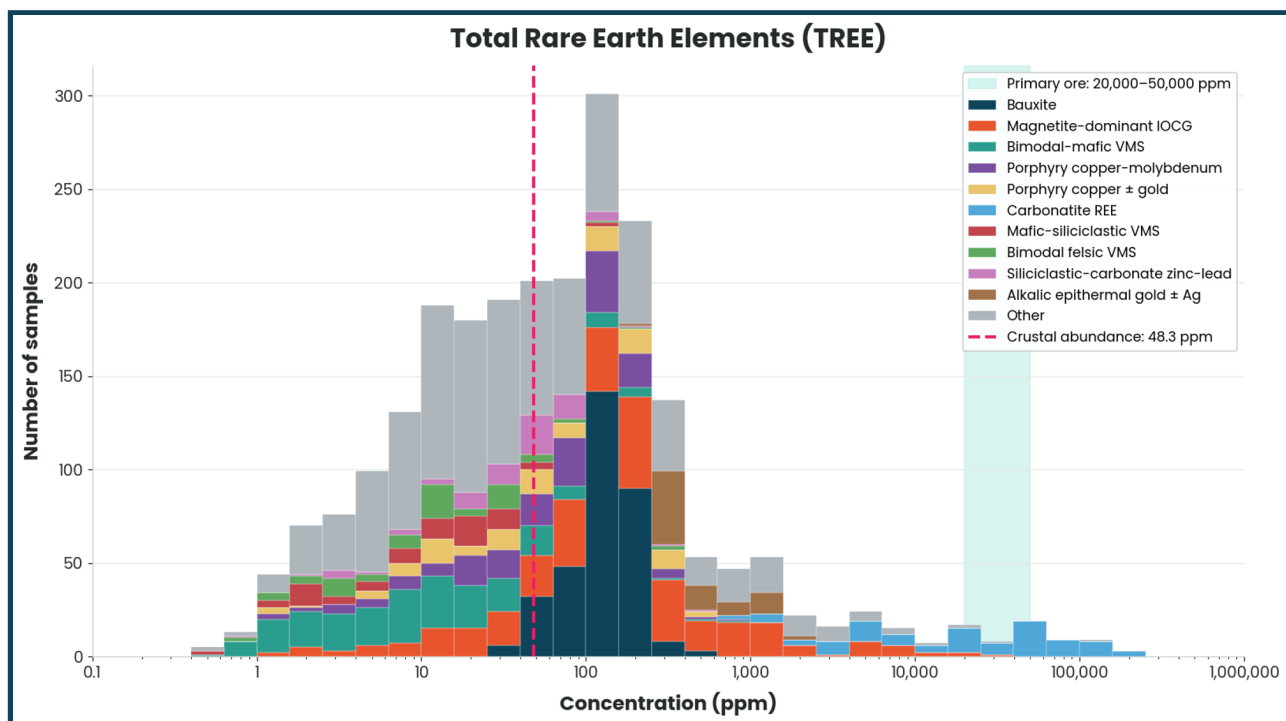


Figure A-30: Policymakers should not expect to source rare earth elements from mine tailings. Carbonatite REE deposits show elevated rare earth element concentrations. However, carbonatite REE mines target rare earth elements and remove them during the milling process.

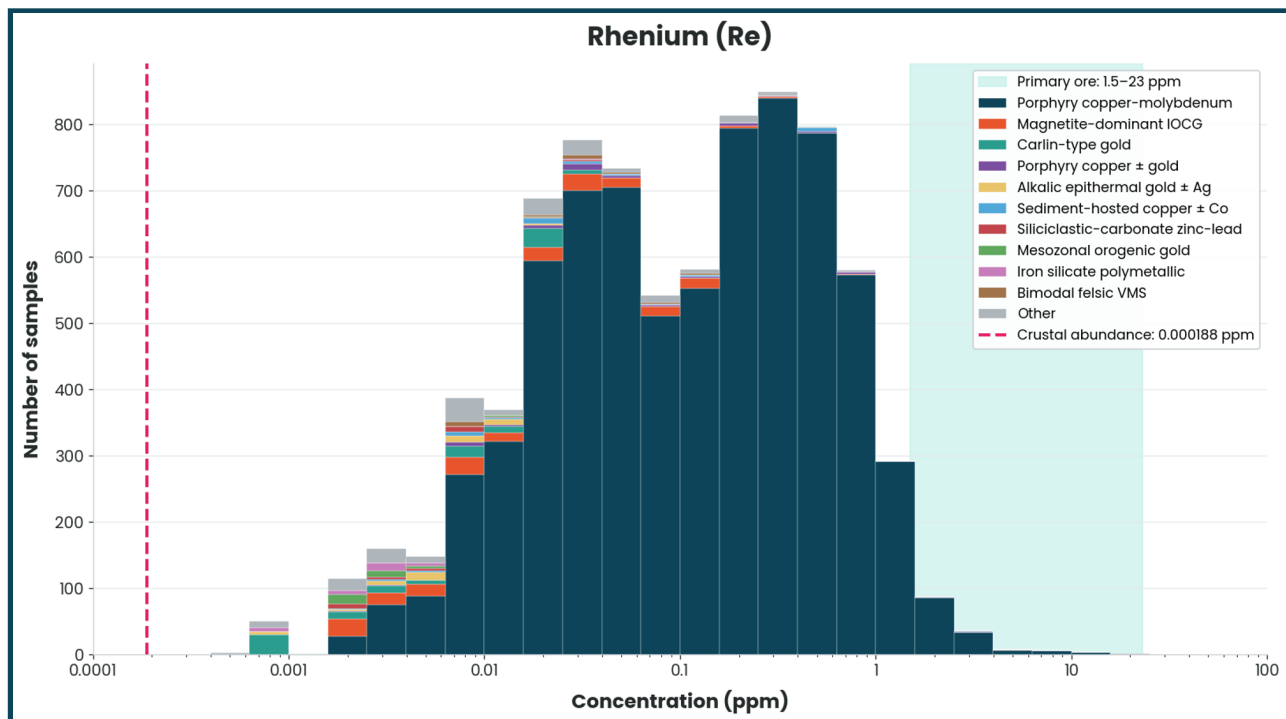


Figure A-31: Policymakers should not expect to source rhenium from mine tailings. Rather, policy initiatives should facilitate the recovery of rhenium from molybdenum smelter waste which serves as the principal production route for rhenium and offers proven extraction methods.

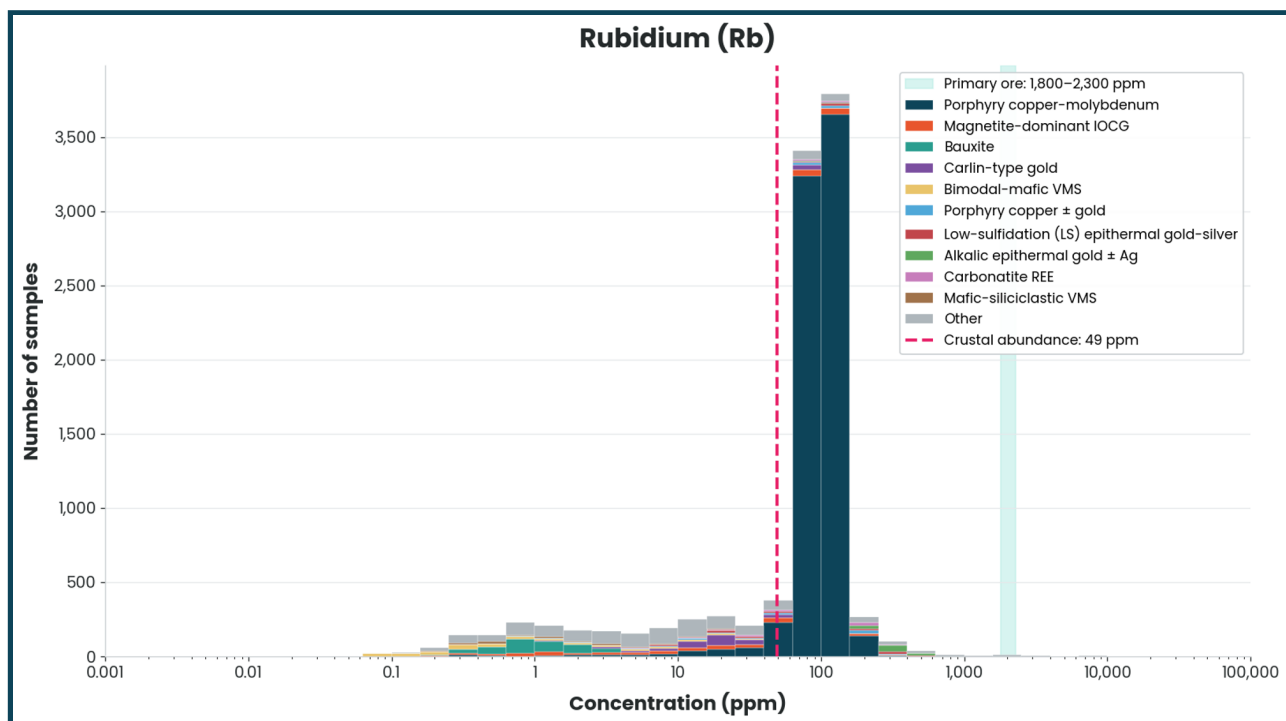


Figure A-32: Policymakers should not expect to source rubidium from mine tailings. Rather, policy initiatives should facilitate the recovery of rubidium from lithium and cesium refinery wastes which serve as the principal production routes for rubidium and offer proven extraction methods.

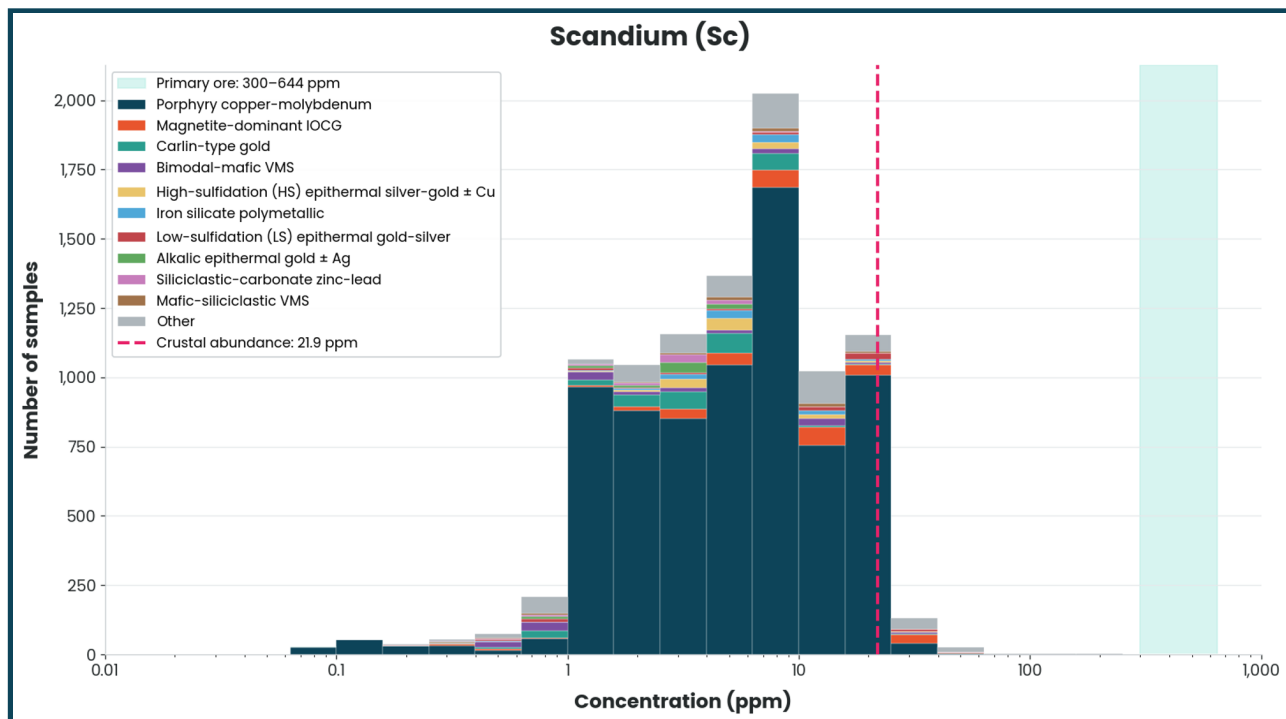


Figure A-33: Policymakers should not expect to source scandium from mine tailings.

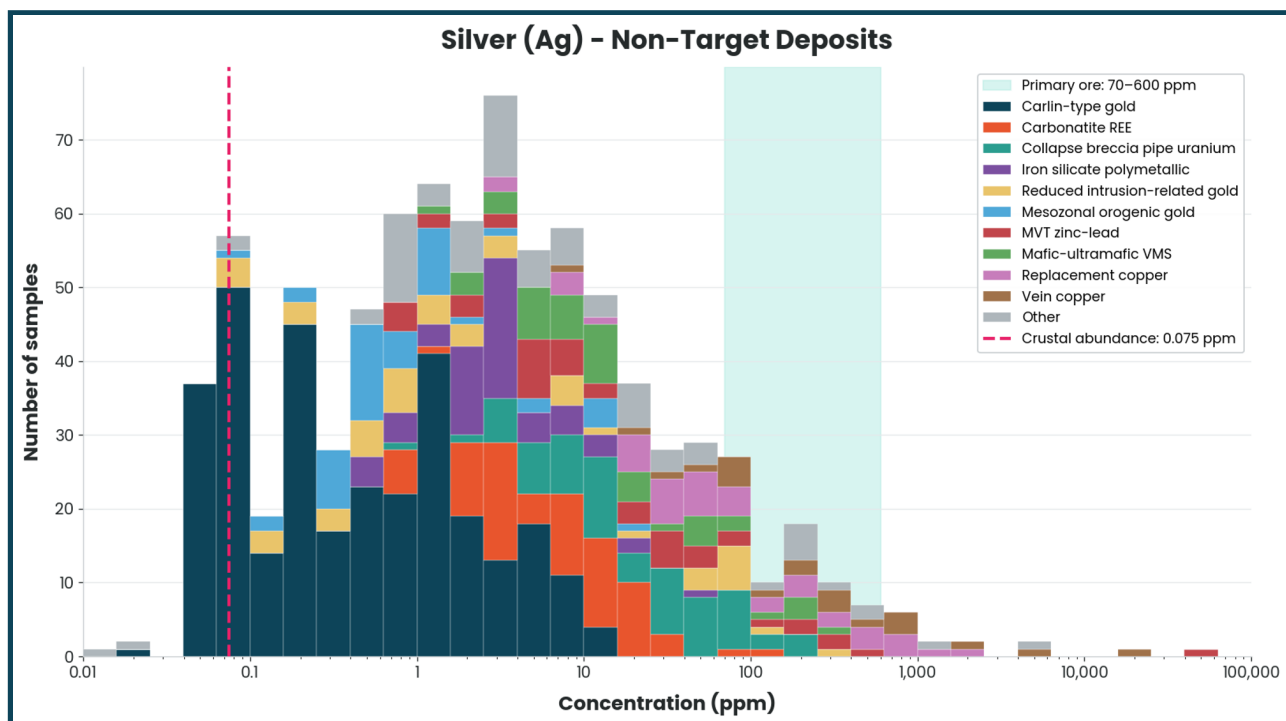


Figure A-34: Opportunities may exist to recover silver from the tailings of vein tungsten mines (shown above under “Other” due to low sample count).

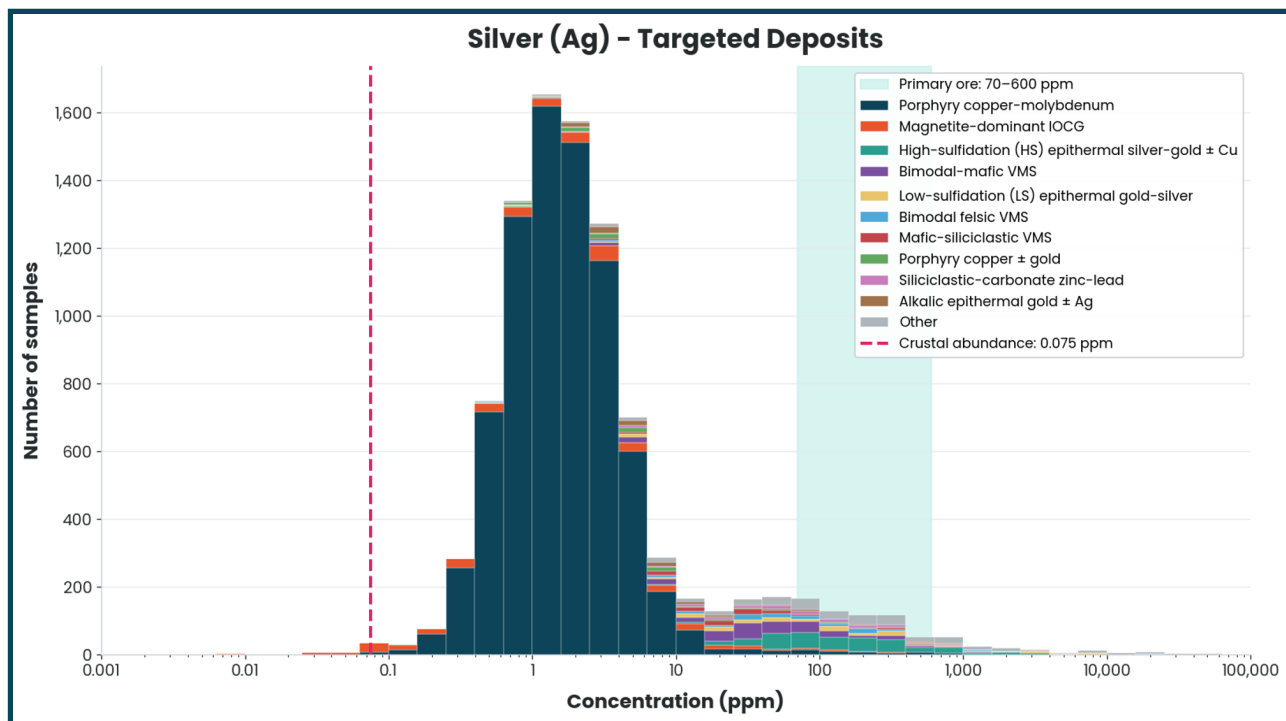


Figure A-35: Silver in the tailings of mines that target silver in reality will occur at much lower concentrations than those shown above since mills recover the silver. Policymakers should not rely on recovering additional amounts of silver from silver mine tailings which remains unlikely and would at best supplement production from new mines.

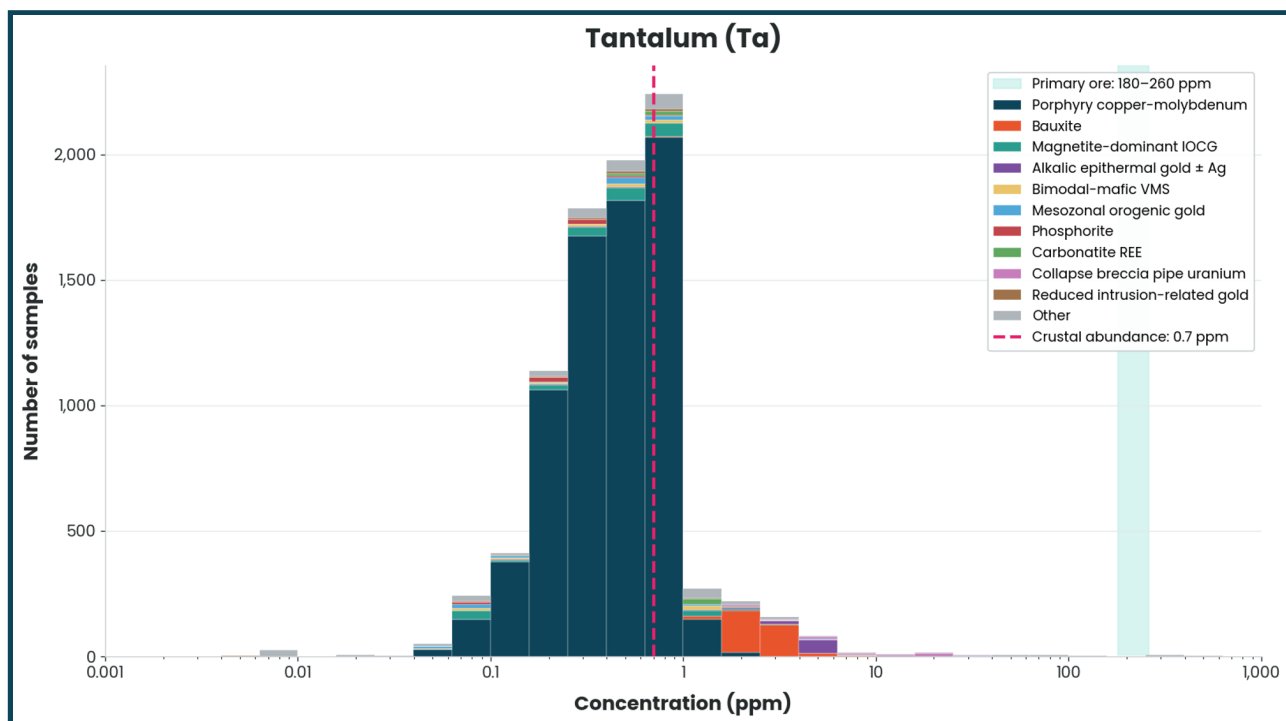


Figure A-36: Opportunities may exist to recover tantalum from the tailings of vein tungsten mines (shown above under “Other” due to low sample count).

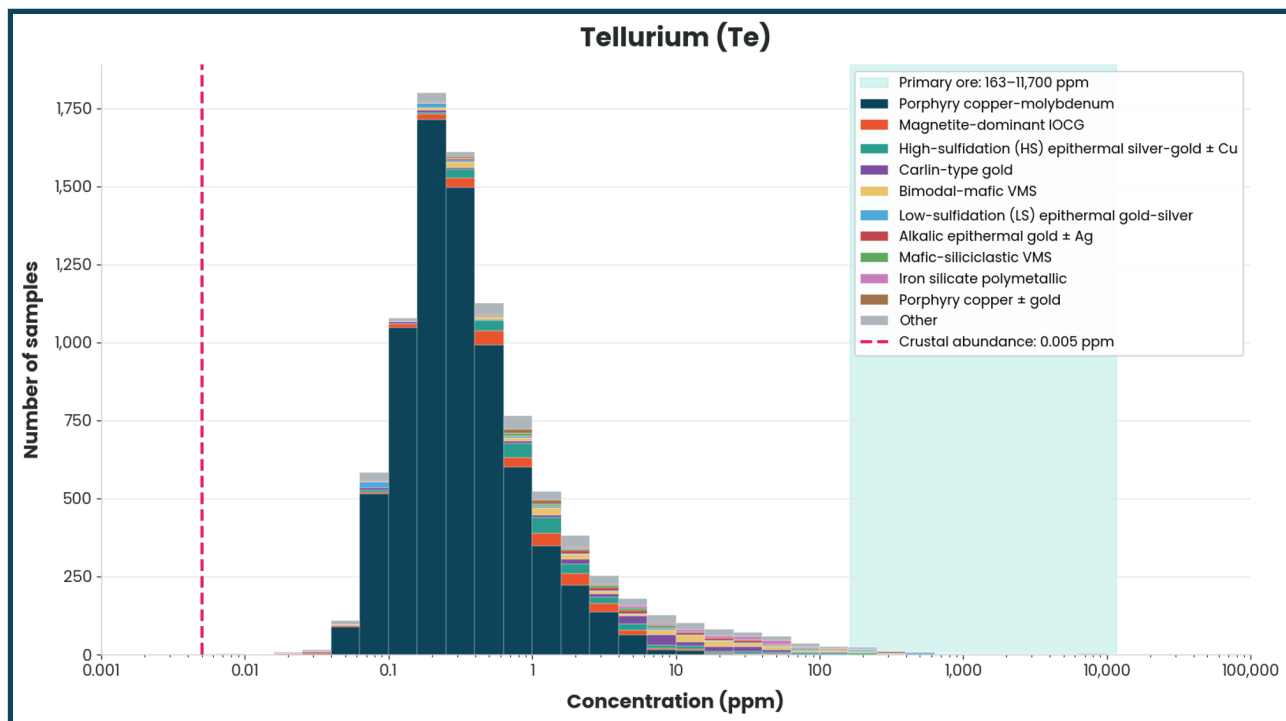


Figure A-37: Policymakers should not expect to source tellurium from mine tailings. Rather, policy initiatives should facilitate tellurium recovery at copper, lead, and zinc smelters and refineries which serve as the principal routes for tellurium production and offer proven extraction methods.

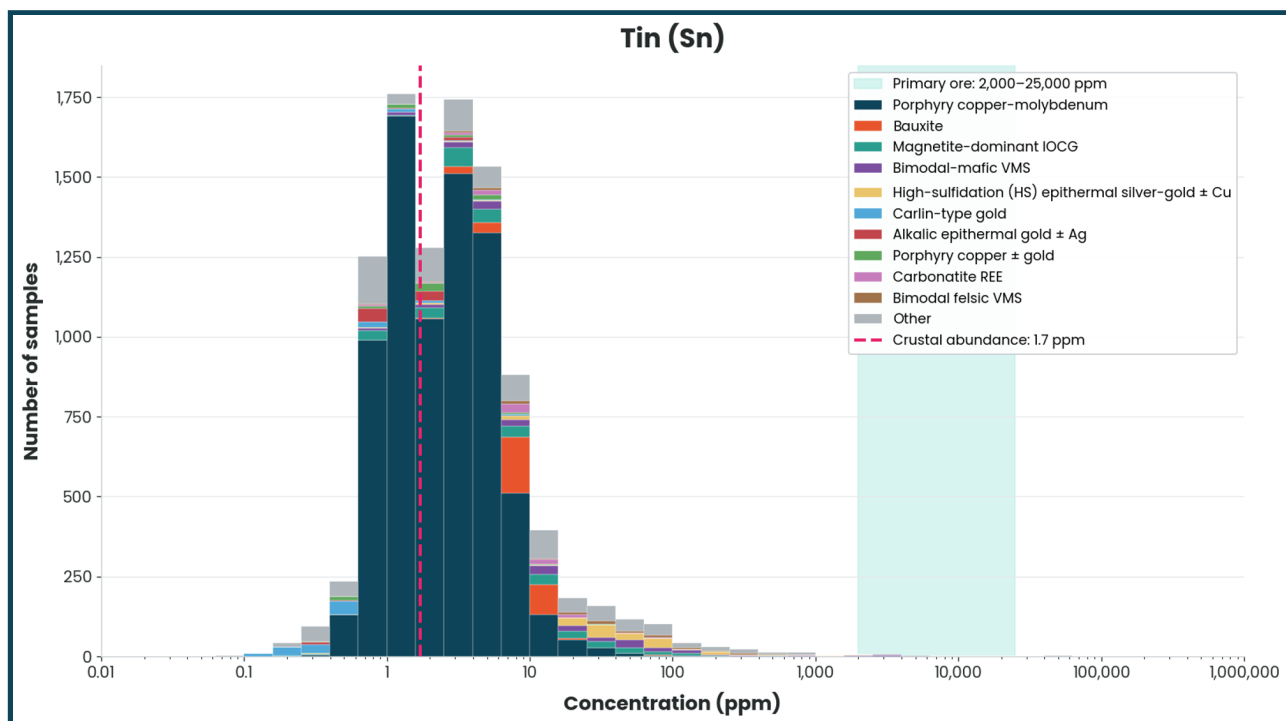


Figure A-38: Policymakers should not expect to source tin from mine tailings.

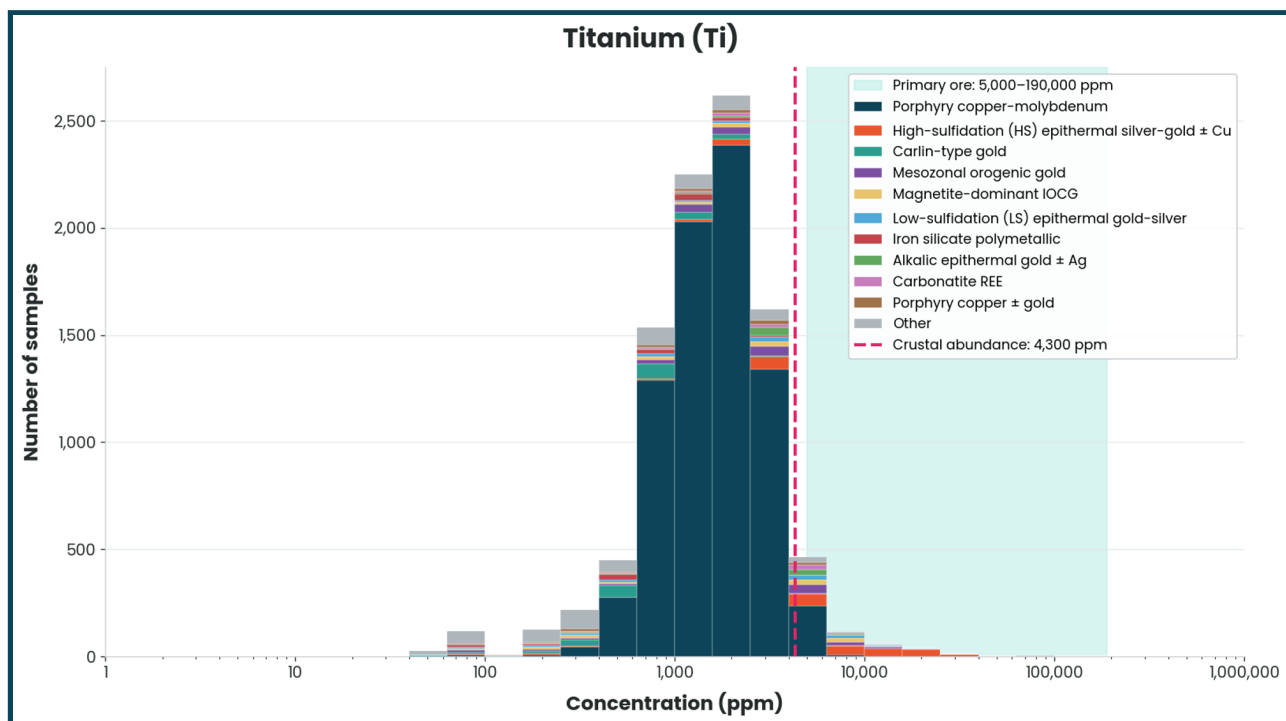


Figure A-39: Opportunities may exist to recover titanium from high-sulfidation epithermal deposit and U-M layered intrusion Ni-Cu-PGE deposit mine tailings (U-M layered intrusion Ni-Cu-PGE shown above under “Other” due to low sample count).

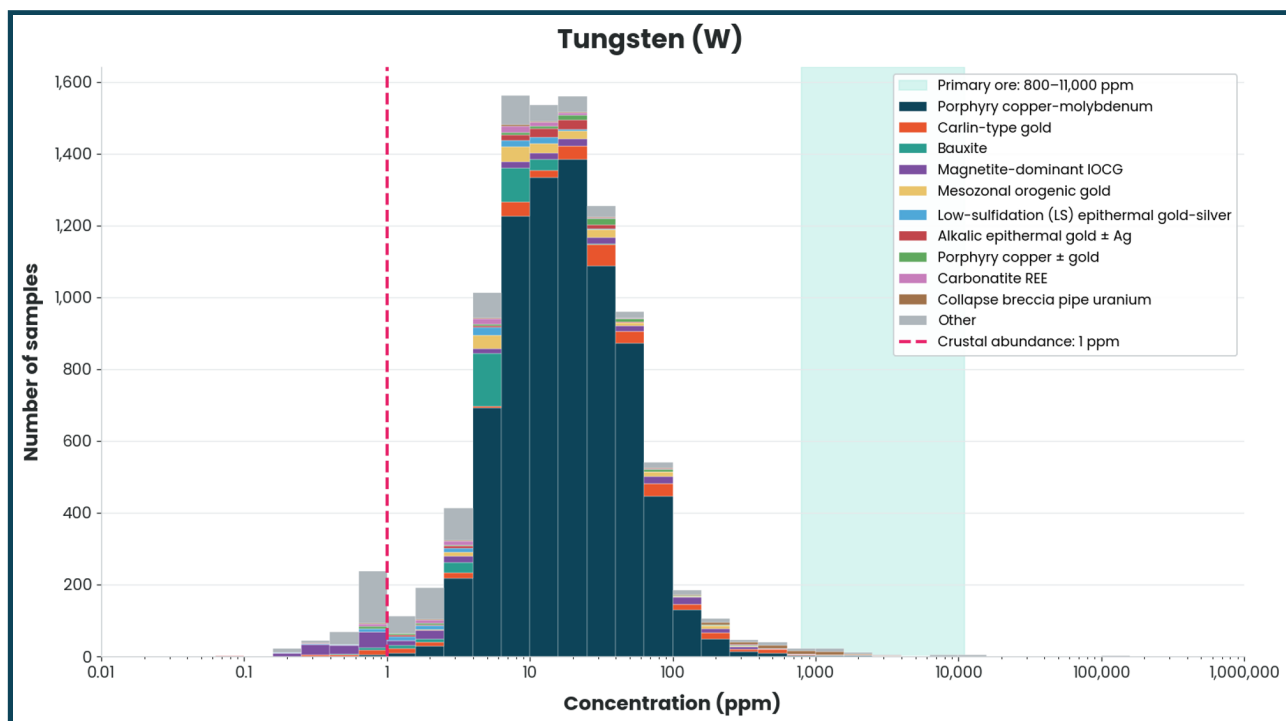


Figure A-40: Opportunities may exist to recover tungsten from the tailings of porphyry tin mines (shown above under “Other” due to low sample count).

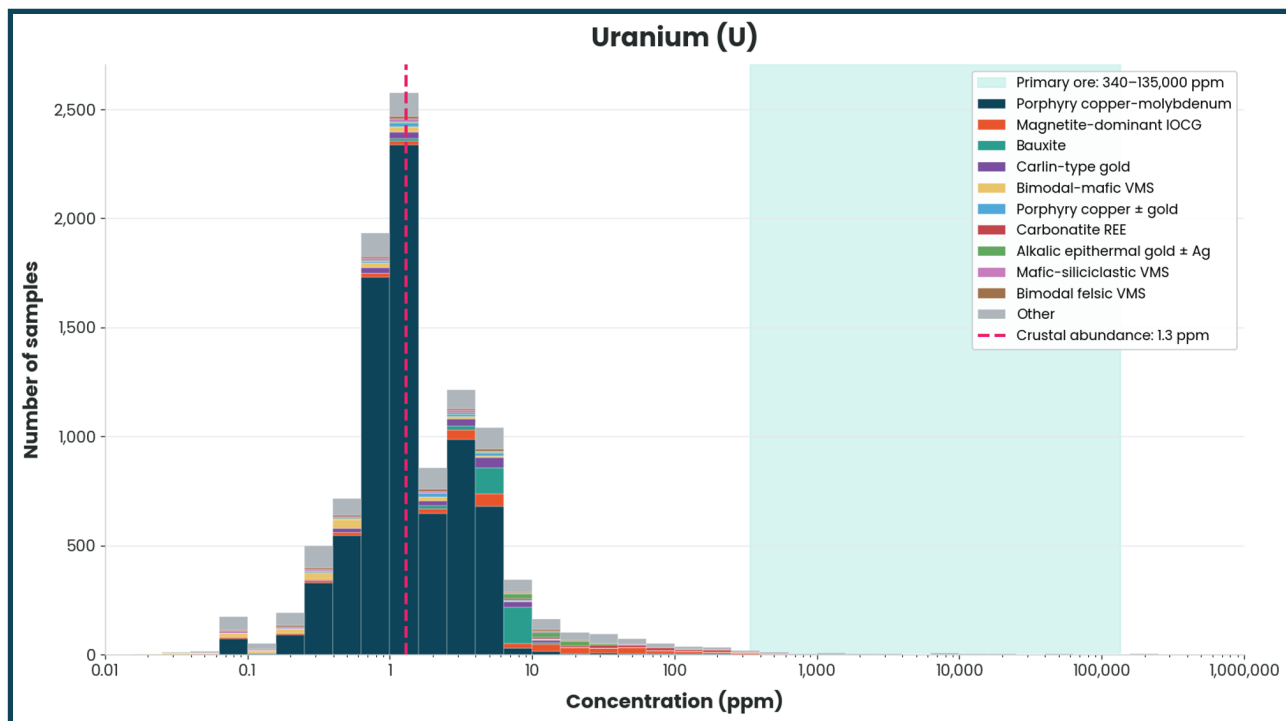


Figure A-41: Policymakers should not expect to source uranium from mine tailings.

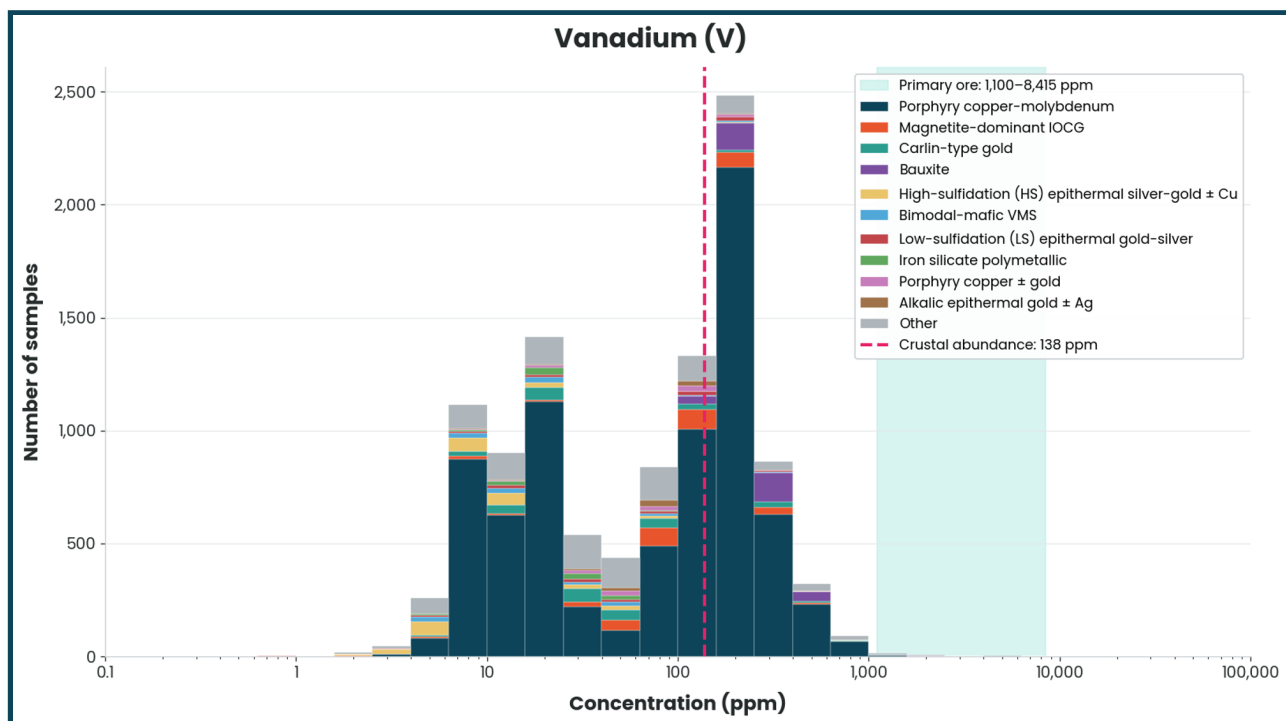


Figure A-42: Policymakers should not expect to source vanadium from mine tailings.

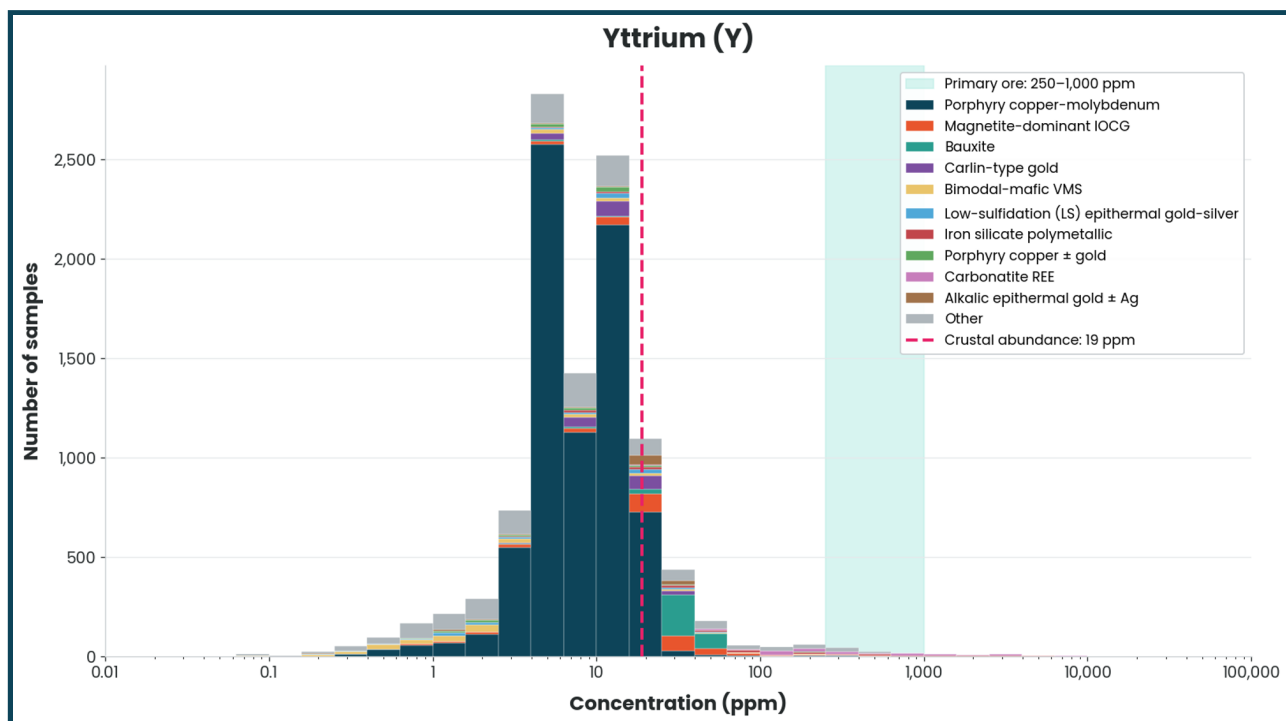


Figure A-43: Opportunities may exist to recover yttrium from vein tungsten deposit mine tailings (shown above under “Other” due to low sample count). Carbonatite REE deposits show elevated yttrium concentrations. However, carbonatite REE mines target yttrium and remove them during the milling process.

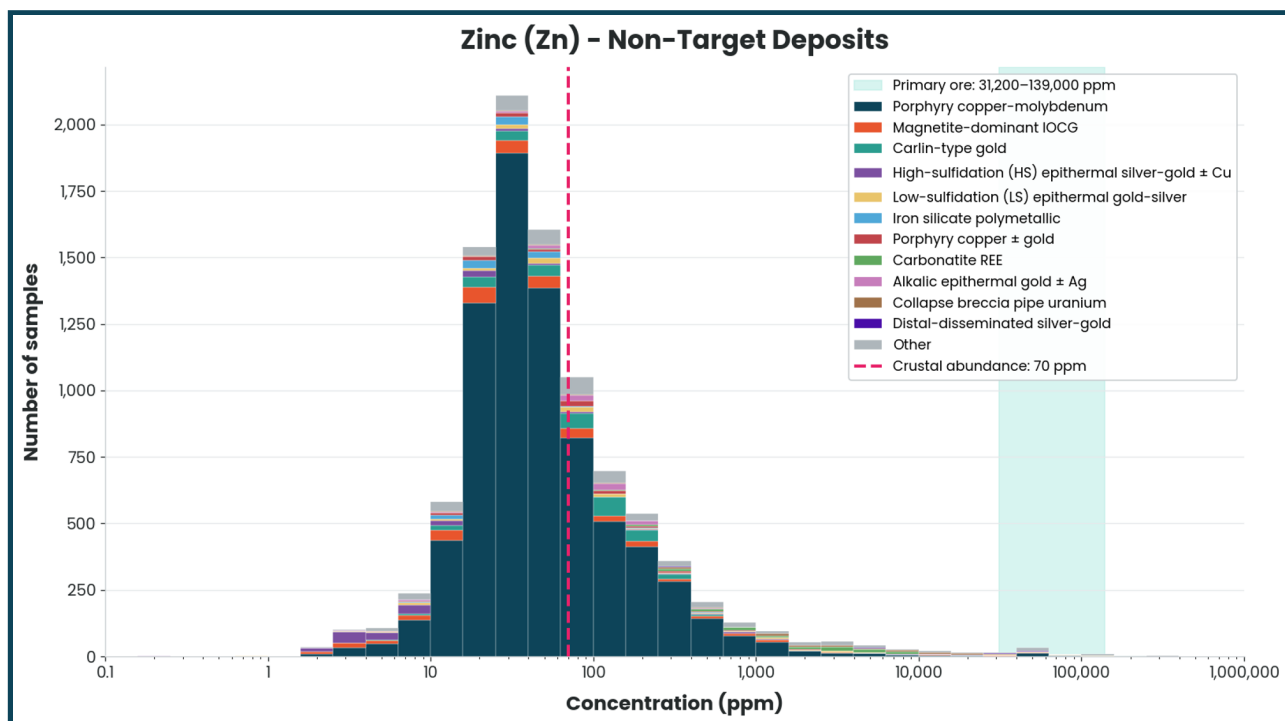


Figure A-44: Opportunities may exist to recover zinc from the tailings of distal-disseminated silver-gold mines.

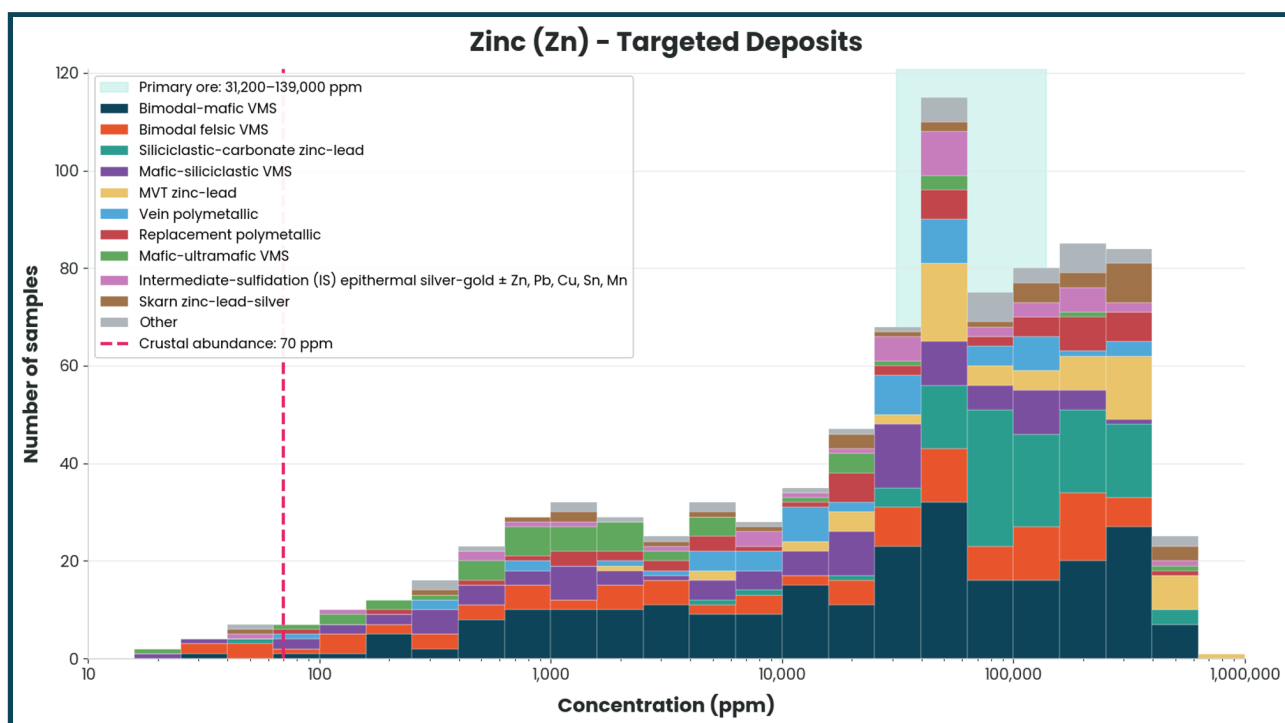


Figure A-45: Zinc in the tailings of mines that target zinc in reality will occur at much lower concentrations than those shown above since mills recover the zinc. Policymakers should not rely on recovering additional amounts of zinc from zinc mine tailings which remains unlikely and would at best supplement production from new mines.

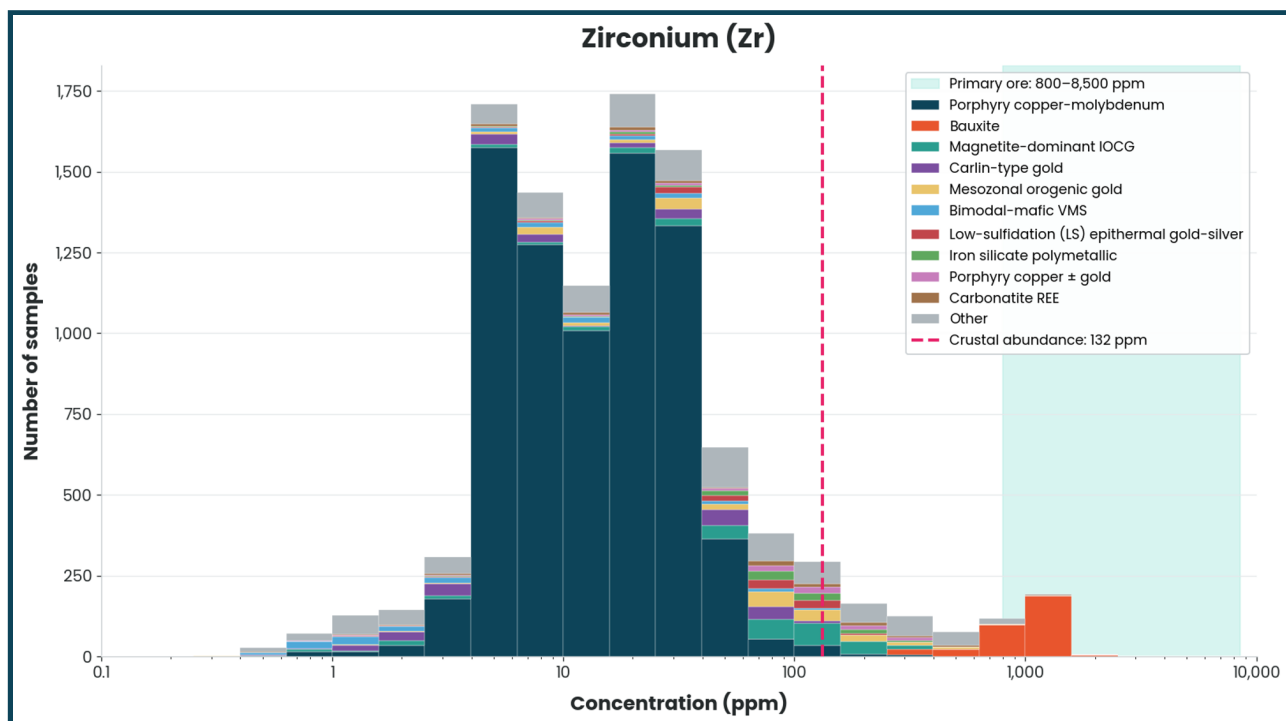


Figure A-46: Opportunities may exist to recover zirconium from bauxite mine tailings or alumina refinery residue.