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The world's by-product and critical metal resources part II: A method for quantifying the resources of rarely reported metals

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ABSTRACT

Estimates of the world's mineral resources of numerous by-product metals remain highly uncertain at best, despite the high criticality of many of these elements to society. This stems from the limited reporting of the concentrations of these elements within mineral deposits by the mining industry, meaning that we require methods to estimate the availability of these resources that overcome this limitation. Here, we present a method for quantifying poorly reported mineral resources of by-product metals that builds upon deposit-by-deposit approaches to global resource estimation, arguably the best-practice approach for well-reported commodities, but also adds the use of proxies for by-product grade estimation. This proxy method allows for deposits with known or inferred by-product metals to also be incorporated within global resource estimates and provides a greater basis for assessing future supply potential.

We demonstrate the application and verification of this methodology with indium, a critical metal for which <1% of identified zinc, tin, and copper deposits potentially hosting indium mineralisation report grades using CRIRSCO (or equivalent) mineral resource reporting codes. The use of the method outlined in this manuscript will allow the global resources of any metal commodity, especially the often under-reported by- and co-product metals that are becoming increasingly essential to modern life, to be quantified to a significantly greater level of accuracy and precision than is allowed by other approaches.

1. Introduction

Entire periods of history have been named after the use of metals like bronze or iron, however we are now seeing changes in which metals are most important to society within lifetimes. This is primarily due to the technologies we use daily becoming more complex and increasingly requiring unique metals to fulfil highly specialised functions (e.g. germanium (Ge) in fibre optic systems or indium (In[2]) in LCD displays). Many of the metals prevalent in modern technology are subject to complicated supply chains, and hence some governments and institutions have begun to consider the criticality of these metals (BGS, 2015; USDoE, 2011; Jowitt, 2015; Skirrow et al., 2013) by quantifying their relative supply risks, importance to society and the environmental implications of their extraction (Graedel et al., 2012). Assessments of criticality have revealed a number of metals as being "most critical" (e.g. USDoE, 2011; BGS, 2015; Skirrow et al., 2013), potentially requiring metal-specific policy interventions in order to avoid or minimise the risk of supply restrictions. These interventions require a better understanding of critical metal resources and supply dynamics; however the reserves and resources of many critical metals remain highly uncertain (Mudd et al., in press-a).

A major factor contributing to this uncertainty is that virtually all critical metals are extracted from mineral deposits as by-products of zinc (Zn), lead (Pb), copper (Cu), nickel (Ni), iron (Fe), titanium (Ti), aluminium (Al), gold (Au), platinum (Pt) and tin (Sn) (Nassar et al., 2015). Although the by-product elements (e.g. indium, Ge, gallium (Ga), selenium (Se) and tellurium (Te)) have significant technological value, they are typically of lesser economic value than the main products of a given mining operation. They are therefore less likely to form part of a company's core business, and hence to be extracted (Willis et al., 2012). With few incentives for mining companies to report the presence of metals that have minimal value to them, there is a global lack of reporting of potential co-products or by-products using mineral resource reporting codes (e.g. JORC, SAMREC, NI 43-101). This is the focus of part I of this study (Mudd et al., in press-a), where we discuss the implications of this lack of reporting and the challenges and uncertainties this absence of reporting has created for global mineral resource accounting, especially of the critical metals. Here, we build on this by presenting a new approach to resource estimation which explicitly

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[2] Although the chemical symbol for the majority of elements are used throughout this paper, we have elected mostly to spell out indium to avoid confusion with the word "in" or the abbreviation of the natural logarithm, "ln".

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addresses the identified uncertainties in order to provide better global resource estimates of by-product and critical metals.

Notwithstanding reporting limitations at the deposit level, numerous attempts have been made to estimate global mineral resources of by-product and critical metals using a number of differing approaches:

- Using reports derived from geological surveys or government mining/resource departments. Such reports have had a tendency to underestimate critical metal resources and often provide little indication of data provenance or uncertainty, although some reports, e.g. by the United States Geological Survey (USGS, 2015a) report/speculate on undiscovered resources, which may limit the risk of underestimation. The quantities published in these reports have on occasion been misinterpreted as representing total extractable global resources (EGR), inflating fears of resource scarcity through the implication that what isn't reported doesn't exist (e.g. Cohen, 2007; Moyer, 2010).
- Applying factors to crustal abundance figures that scale them to a potential extractable resource volume (see UNEP et al., 2011). Measures of a metal's crustal abundance (e.g. grams metal per tonne of the Earth's crust) provide a very coarse indication of the total amount of a metal in the lithosphere. A fraction of this volume is concentrated to economic or sub-economic locations, referred to as reserves and resources, which have clearly defined definitions that are strongly tied to the economics of extraction. Mineralising systems classified as reserves and/or resources are, by definition, anomalous, and so it is methodologically flawed to assume that they can be indicated by crustal abundances. This approach also neglects to consider the mineralogical barrier that was first introduced by Skinner (1976).
- Assuming a fixed ratio between a base metal and a by-product; for example, considering that 50 g indium is present per t Zn within Zn sulphide ores (see Schwarz-Schampera, 2014). This approach may neglect geological variability, for example between deposit types, especially when considering that a single project could contain multiple different deposit types with differing geological and grade characteristics (e.g. Jowitt et al., 2013), and hence most likely differing relationships between base and by product metals. However, this approach can be adapted to be deposit type specific and allows for the quantification of uncertainty, as is well demonstrated by Frenzel et al. (2015), who present an analogous approach using Ge assumed to be contained within sphalerite in Mississippi Valley Type (MVT) deposits. This approach does not necessarily require the use of mineral resource reporting codes to determine the tonnage of critical metal-bearing orebodies.
- Constructing a database of deposits with the reported quantities of the metal in question using mineral resource reporting codes (e.g. cobalt (Co) as a co-/by-product of Ni is well reported and an ideal critical metal for this approach; see Mudd et al., 2013b). This approach is arguably the best practice in mineral resource accounting, and directly indicates resources known to the mining industry to be extractable. It does not, however, explicitly overcome the limitation of reporting, and is likely to only reflect a small portion of the EGR for most critical metals.

Each of these approaches has strengths and weaknesses. However, to the best of our knowledge, no approach has produced global resource estimates that combine:

- Resource assessments based on per-deposit estimates made using mineral resource reporting codes for orebody tonnage (ensuring that resource assessments are restricted to those deposits with known or inferred by-product mineralisation),
- The quantification and/or classification of uncertainty, and
- A direct method of addressing the lack of by-product reporting at the per-deposit level.

Here, we present the Proxy Method, an approach that combines all of these factors and is reproducible for any by-product metal. We demonstrate the efficacy of this approach by applying it to indium, a critical metal for which <1% of identified Zn, Sn, and Cu deposits potentially hosting indium mineralisation report indium grades using CRIRSCO mineral resource reporting codes (see Werner et al., 2016). Our proposed methodology builds upon the methods applied to resource assessments of other primary commodities, including Ni (Mudd and Jowitt, 2014), Cu (Mudd et al., 2013a), Co (Mudd et al., 2013b), REEs (Weng et al., 2015), Au (in prep.) and Pb and Zn (Mudd et al., in press-b), making maximum use of reserve and resource data from CRIRSCO code-based reports. This ensures that considering the world's resources of a given by-product metal uses estimates that are constrained to the small portion of the earth's crust already known to the mineral industry to contain economic or near-economic quantities of host metals from which by-product extraction can be economically leveraged. The processes introduced in the following sections highlight how proxies may be used to infer by-product grade estimation, and how statistical analysis for the quantification of uncertainty can also be embedded into this approach.

2. General design

Our methodological approach aims to produce a comprehensive list of deposits with known or inferred mineralisation of a metal, and to quantify the amount of that metal in each deposit using the best available information. The summed total of per-deposit quantities then represents a new global resource estimate. Depending on the quality of information available, by-product or critical metal resources will have to be determined differently for each deposit. Some deposits may be quantified directly from publicly available information; however, given the limited state of critical metal reporting in mineral resources by deposit, the majority must be quantified through the use of proxy data. Three types of proxy are introduced in this paper that permit by-product metal grades to be estimated, although our approach does not limit the number or type of proxies which can be applied as long as they permit the estimation of by-product metal grades by some justifiable means, allowing new information to be incorporated into the estimation process as it becomes available. Our approach is summarised in Fig. 1 and explained further in the following sections.

3. Reported resource data collection

Our approach first requires that reported data be collected and developed into a resource database. This process entails an extensive review of mining company websites, technical reports, published literature, mineral resource atlases and other national/state mineral occurrence databases with information on mineral deposits containing the by-product element of interest. Any deposit where geological testing notes the by-product as a commodity or potential commodity is added to a list. This review process must be guided by a reasonable understanding of the geology and production characteristics of the metal of interest. For example with indium, which we consider as an example in the following sections, production comes exclusively as a by-product of Zn, Sn and Cu mining, with Zn being the primary source (>95% of global indium production; Schwarz-Schampera, 2014). This is consistent with the strong mineralogical relationship indium shares with Zn (Cook et al., 2011a; Werner et al., 2015), suggesting that deposits with currently known economic quantities of Zn most likely also contain indium, even if not explicitly reported. This understanding enables the efficiency of the review process to be improved.

If a host metal such as Zn is reported as a commodity using CRIRSCO mineral resource reporting codes, there is greater likelihood that the extraction of a by-product can also be economically leveraged. The full list of potential indium-bearing deposits (see the Supplementary data and the Part III paper, Werner et al., 2016, for further analysis) contains entries where the presence of indium is either explicitly reported or is inferred through its mineralisation and reported presence of host metals.