



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.

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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 (In²) 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”.

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.

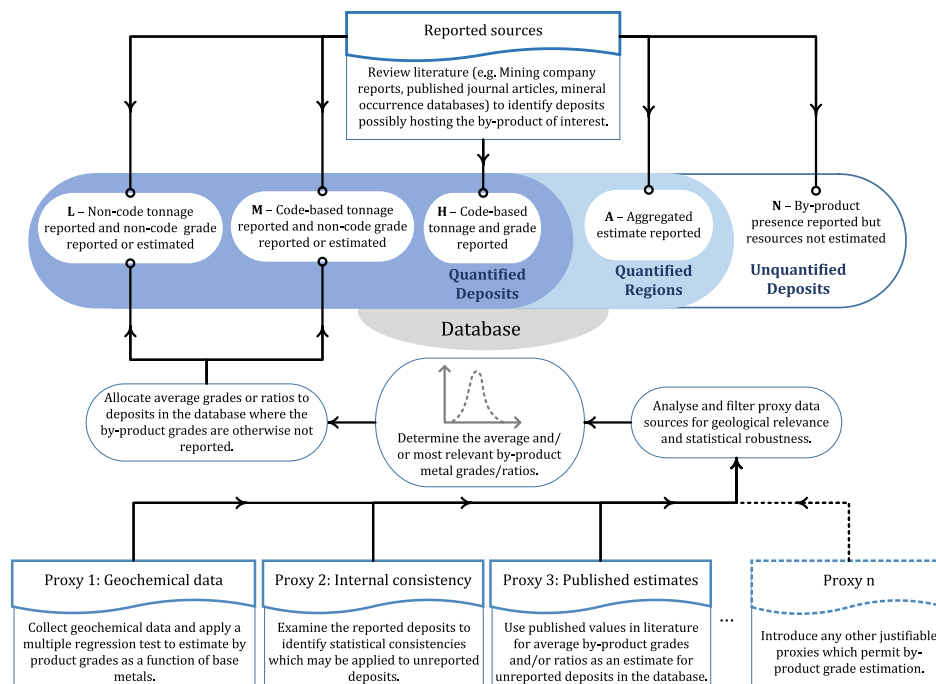


Fig. 1. General method outlined in this study, involving the use of a combination of reported data and proxy data to construct a per-deposit resource database, which itself is organised into differing classifications (quantified deposits, quantified regions and unquantified deposits) and levels of certainty (high, medium, low and aggregated estimates, plus unquantified deposits). Proxy data sources are employed to estimate by-product metal grades where they are otherwise not reported by mining companies or in related literature.

The results produced using this approach can generally be organised according to this distinction of reported vs. inferred deposits. Given the strong association between indium and Zn, the list of inferred deposits used for our indium study were primarily obtained from a collected database of global Pb–Zn resources (Mudd et al., in press-b). The indium in many Pb–Zn deposits with inferred indium mineralisation is unlikely to be economically extractable at present, though in the event that indium prices increase and/or supply becomes restricted through conventional production pipelines, this may change. An economic assessment of by-product/critical metal potential is not the focus of this methodology, rather the estimation of sheer resource quantities in known deposits, which may then support such assessments. We include these currently sub-economic quantities in our database to ensure that the results remain relevant regardless of future price changes. A table documenting 98 deposits reporting a total of ~74,600 t indium is provided in the Supplementary data, and should be considered as additional resources to those presented in the following proxy analysis.

4. Evaluation of resource data quality

When tasked with the quantification of by-products/critical metals within each identified deposit, it is recognised that data quality will vary. A grading system, described as follows, establishes a hierarchy of certainty upon which the resource data are to be interpreted for each deposit or each estimate. It has been developed from an earlier scheme described in Mudd et al. (2013b):

High quality (H): The by-product resource for the deposit has been reported based on the most recent statutory code-based resource estimate available, which contains both a resource tonnage and associated grade. This indicates that the resource estimate for this site has been determined based on a rigorous exploration and resource assessment process, and is representative of the size of the extractable orebody. The values presented under this classification should therefore be considered the most accurate.

Medium quality (M): A recent statutory code-based assessment for the deposit is available to determine the size of the orebody. Yet despite reports of the presence of the by-product at this site, or high likelihood of it being present due to mineralogical associations, no code-based grade estimate is available. The grade of the by-product must be determined through the use of a non-code source or using the proxies described in Section 5. In cases where a low quality estimate is available but a code-based orebody tonnage is also available, the code-based tonnage is applied to update the status of the orebody and the deposit is classified as medium quality. A separate classification, “Medium-calculated” (Mc), may be applied to deposits where the by-product grade has been calculated using the proxies of this study (as per Fig. 1), and applied to a deposit with code-based tonnage.

Low quality (L): Neither by-product grades nor orebody tonnage are available for the deposit under a code-based classification scheme. Grade and tonnage are determined from geological publications, industry and government reports, academic theses or similar works. The data from these publications are not necessarily low quality in themselves, however the database entry receives this classification as it cannot be determined whether the grade and orebody tonnage are truly representative of the mineralising systems. A separate classification, “Low-calculated” (Lc), may be applied to deposits where the grade has been determined from the results of proxy estimation, and applied to a deposit with non-code-based tonnage.

No resource estimate available (N): The deposit has been noted in the literature reviewed for being particularly enriched in the by-product metal in question, although no resource estimates for the orebody have been identified by the authors, and/or insufficient information is available to infer by-product resources using proxies.

Aggregated resource estimate (A): This resource estimate may represent multiple deposits, and/or is representative of a broader region in which by-product resource data were available. The quality of

these estimates are to be considered at or below “L”, but are included for completeness and representativeness of the literature.

Through the summation of reported and semi-reported quantities of the by-product in identified deposits classified as high, medium and low, a view of the global resource in extractable locations is provided. An additional sense of the scale of potential future resources is provided by the number of deposits classified as ‘N’ and ‘A’.

5. Proxies for grade estimation: case study of global indium resources

Deposits with reported tonnages but unreported by-product grades require a proxy to infer the abundance of the by-product within the deposit. As shown in Fig. 1, three distinct proxy approaches are described in this study. These approaches introduce an additional suite of literature and databases and may be used to classify additional deposits as “M” and “L”, depending on the existing quality of tonnage data for the deposit in the database. Using indium as an example, the proxies are described as follows:

5.1. Proxy 1: geochemical databases and multiple regression

This first approach considers that in terms of mineralogy and production, it is possible to find strong statistical and physical links between indium and some common metals (Werner et al., 2015). Similar links have also been found in terms of grades, suggesting that at some level, the grades of metals likely to be reported may indicate unreported indium grades. Table 1 summarises those studies which have considered this through grade relationships between indium and other metals in mineral deposits.

While these studies all affirm some link between indium and one or more metals, they have varying findings that are difficult to consolidate. Hence, they collectively highlight that it can be problematic to infer indium grades for a diverse deposit database based on individual deposit studies, and based on links with a single base metal.

Table 1

Review of literature analysing inter-element relationships between indium and common metals.

Correlation found with indium	Reference
The In/Sn ratio varies from <0.1 to 47 in sulphides.	Yi et al. (1995)
Indium is found when Pb–Zn deposits are Sn rich. Eighty percent of indium in Chinese deposits can be found within the mineral sphalerite (ZnS).	Qian et al. (1998)
Multiple regression coefficients used to accurately determine indium grade, based on base metal grades and the proportion of different minerals present in ore at Neves Corvo, Portugal. Strong associations observed between Sn/stannite (Cu ₂ FeSnS ₄).	Benzaazoua et al. (2002)
In samples of Japanese ore of varying deposit classifications, indium was found to correlate best with Sn, then Ga, and most poorly with Zn.	Ishihara et al. (2006)
Indium becomes relatively more abundant in cases where Cu contents are high and Zn contents are low. This study otherwise provides a good summary of indium mineralogy.	Cook et al. (2011b)
From studies at the Pinguino deposit in Argentina, indium can be strongly correlated with Sn in early stage mineralisation, and with Zn in later stage mineralisation.	Jovic et al. (2011)
Indium correlations were generally low among base metals in ores of the Dulong and Dachang mines, China, however the best correlation was found with Zn.	Ishihara et al. (2011)
The 1000 In/Zn ratio in sphalerite can be a useful indicator of the grade of In in the deposit overall. However, the proportion of sphalerite must be known, which appears not to be widely reported.	Murakami and Ishihara (2013)
In metamorphosed sulphide deposits, strong correlations can be found between indium and Cu, supporting the coupled substitution model.	Lockington et al. (2014)

These studies are therefore not directly applied as proxy data sources. To find more general orebody relationships that could be applied to a diverse deposit database, we collected and analysed large geochemical databases that a) documented the occurrence of indium, b) documented the occurrence of other metals associated with indium in terms of mineralogy or production (i.e. Zn, Sn, Cu, Pb, Au, Pt, iron (Fe), bismuth (Bi), sulphur (S), cadmium (Cd) and arsenic (As)), and c) encompassed multiple deposit types or geological settings. These databases included:

- FOREGS Geochemical Atlas of Europe (Salminen et al., 2005)
- Geochemical Atlas of Australia (de Caritat and Cooper, 2011)
- SedDB – Earthchem.org (Johansson et al., 2012)
- GEOROC (47 individual sources listed from online query for Cu, Sn, Pb, Zn, Bi, silver (Ag), Pt, Fe, S, Cd and indium in whole rocks, sourced via <http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp>)
- USGS National Geochemistry Database: Rock (USGS, 2015b)
- OSNACA (Ore Samples Normalised to Average Crustal Abundance, Brauhart and Hagemann, 2011)
- Sulphide Ore Geochemistry Database for Volcanogenic Massive Sulphide Deposits of the Paleoproterozoic Flin Flon Belt and Sherridon Area, Manitoba and Saskatchewan. Geological Survey of Canada (Jonasson et al., 2009)
- Geoscientific Data Warehouse mineral resource drilling database, New South Wales, Australia (DIRE, 2016)

Not all geochemistry databases collected were found to contain indium data. For example, a whole rock geochemistry database of Australia (OZCHEM, Champion et al., 2007) was found not to contain any data for indium from over 32,000 data points. Similarly, sources of drillhole assay datasets such as the Geoscientific Data Warehouse for New South Wales, Australia, contain hundreds of thousands of geochemical measurements, but as indium and many other critical metals are not commonly assayed (see also DNRM, 2014), they often cannot provide many data points. As shown later in Table 2, we have managed to find only 51 useful data points from this source. Other databases, sometimes covering the same geographical regions, were however found to be more useful. For example, an assessment of surface geochemistry in Australia (from the Australian Geochemical Atlas) showed that a total of 7902 data points contained 5320 samples with indium concentrations. These data are not sufficient to directly infer average ore grades as they represent surface geochemistry and have similar issues to the crustal abundance approaches outlined above; however, these data may be able to provide an indication of the statistical relationship between elements, which itself can be a reflection of the geochemistry at greater depths (Bradshaw et al., 1974). For this particular database, indium weakly correlates with Zn despite its strong association in terms of production (see Werner et al., 2015), but strongly correlates with Sn (Fig. 2). This may be a function of surficial/regolith processes, where Sn is less mobile than Zn (see Smith and Huyck, 1999).

The fact that higher grades of Sn are associated with higher grades of indium within anomalously enriched samples (i.e. samples most likely related to mineralisation) at the continental scale suggests that this correlation may be used to more accurately estimate the grade of indium where Sn grades are reported. This finding is akin to some studies listed in Table 1, however, Sn itself may not always be reported, suggesting that a correlation which takes into account all potentially reportable base metals which host indium mineralisation, as well as those elements which form minerals with indium has greater utility. Multiple regression techniques provide equations that describe indium grade as a function of multiple element grades. The indium equation generated from each examined database took the general formula:

$$\text{Ingrade (g In t}^{-1}\text{)} = \sum_{i=1}^{i=n} (x_i \cdot h_n) + c \quad (1)$$

Table 2

Summary of geochemical databases analysed for indium content and statistical reliability.

Geochemical database	Description	No. of useable indium-containing measurements	Elements incorporated into regression (in order of statistical significance)	R^2	Average error	Pass Y/N
GEOROC	"A comprehensive collection of published analyses of volcanic rocks and mantle xenoliths." — Whole rock samples analysed.	55	Sn, Zn, Cu, Ag, Pt, As, Pb	0.953	5%	Y
Forum of European Geological Surveys (FOREGS) Geochemical Atlas of Europe	Geochemical survey of European floodplain sediment, humus, soil, stream sediment and stream water. Subsoil dataset analysed.	785	Ag, Fe, As, Cd, Sn, S, Cu, Zn, Pb	0.315	41%	N
Geochemical Atlas of Australia	Soil/sediment samples gathered from 1315 sites in 1186 catchments across Australia.	1281	Sn, Fe, Cd, Pt, S, Pb, Cu, Zn	0.934	25%	Y
EarthChem.org: SedDB	"SedDB is a data management and information system for marine sediment geochemistry." — indium-containing measurements derived only from whole rock basalt samples	192	Sn, Cd, S, Fe, Ag, As, Zn, Pb, Cu	0.959	3%	Y
USGS: National Geochemistry Database: Rock — ICP-MS ^a	"Geochemical analysis of rock samples collected and analysed by the USGS. This dataset includes and supersedes rock data formerly released as	938	Zn, Cu, Cd, Pb, Fe, Ag, Sn, As	0.937	158%	Y
USGS: National Geochemistry Database: Rock — ES ^a	"Geochemistry of igneous rocks in the US extracted from the PLUTO database".	15,439	Pt, Fe, Zn, Cu, Ag, Sn, As, Pb	0.119	53%	N
USGS: National Geochemistry Database: Rock — Unk ^a		8111	Pt, Cd, Pb, Ag, Zn, Sn, As, Cu	0.271	93%	N
NSW Department of Industry, Resources and Energy — Geochemical Database	Drill core/assay database for mineral deposits in NSW, Australia	51	Cd, Ag, Sn, Pb, As, Zn, Cu, Fe	0.882	98%	Y
OSNACA — sediment-hosted Pb–Zn/Mississippi Valley Type (MVT)	"The OSNACA Project (Ore Samples Normalised to Average Crustal Abundance) is an open source project where assay data is freely available online." — Utilises "representative ore samples" from across the globe. 348 deposits included in our regressions.	33	Cu, Sn, Ag, Pb, Cd, Pt, Zn, As, S, Fe	0.920	426%	N
OSNACA sediment-hosted Pb–Zn/Irish type		17	Cd, Ag, Pb, Cu, Zn, Pt, Sn, S, Fe, As	0.937	53%	Y
OSNACA sediment-hosted Pb–Zn/sediment-hosted massive sulphide		24	Sn, Zn, Fe, S, Cu, As, Pb, Ag, Cd, Pt	0.825	83%	Y
OSNACA — orogenic Au		173	Cu, As, Zn, S, Sn, Cd, Pb, Ag, Fe	0.095	83%	N
OSNACA — skarn		25	Ag, Pb, Fe, Cu, Sn, Zn, Cd, As, S	0.728	77%	Y
OSNACA — epithermal		87	Zn, Pb, Fe, Cu, Ag, S, Pt, As, Sn, Cd	0.779	159%	Y
OSNACA — sediment-hosted Stratiform Cu		30	As, Fe, Sn, S, Cu, Zn, Ag, Cd, Pb	0.868	103%	Y
OSNACA — volcanic massive sulphide (VMS)		90	Ag, Cu, Pb, Fe, Sn, Zn, Cd, As, S	0.352	127%	N
OSNACA — IOCG		31	S, Fe, Cd, Pb, As, Zn, Sn, Cu, Ag	0.706	83%	Y
OSNACA — granite-related		20	Cu, S, As, Sn, Ag, Pb, Cd, Fe, Zn	0.961	62%	Y
OSNACA — porphyry Cu		42	Sn, Fe, Cd, Pb, Zn, S, Ag, As, Cu	0.999	77%	Y
Sulphide ore geochemistry database for volcanogenic massive sulphide deposits of the Paleoproterozoic Flin Flon Belt and Sherridon area, Manitoba and Saskatchewan — Geological Survey of Canada Open File 5432	Data from 40 VMS deposits in Manitoba and Saskatchewan, Canada	350	Cu, Sn, Zn, Cd, Ag, S, Pb, As, Fe	0.328	98%	N

^a ICP-MS = dataset compiled through the application of inductively coupled plasma mass spectrometry. ES = dataset compiled through the application of emission spectroscopy. Unk = unknown methods used to determine quantities presented in this database. Refer to USGS (2015b) for more details.

where x_1 to x_n are the regression coefficients, h_1 to h_n are the measured grades of metals such as Sn, Zn, Pb, Cd, Pt, As, Bi, Fe, Ag, S and Cu (which have production or mineralogical relationships with indium, see Schwarz-Schampera, 2014) and c is the equation's intercept.

The accuracy of this equation was tested to see how well it predicts reported values in the databases listed in Table 2. This entailed applying the equation to all data points and determining the residual values. We chose not to take these residuals directly as indications of error, but rather their percentages, as at higher grades the percentage error will become considerably more relevant than absolute values. For example, if a data point is measured at 0.02 ppm and the equation estimates 0.03 ppm, we take the error to be 33% (calculated from the residual between the predicted and observed values for indium grade as a percentage of the predicted value) rather than 0.01 ppm, as we cannot assume the error to remain this small in magnitude when the equation predicts grades upwards of, for example, 10 ppm per deposit. If an equation was

found to predict indium grades with sufficient accuracy (which we arbitrarily set at $R^2 > 0.70$ and average error < 200%), it was deemed acceptable to progress to the next stage of analysis as a potential proxy data source in our deposit database. The results of this testing are presented in Table 2, which shows that the strongest relationship between base/mineral-forming metals and indium was found in the OSNACA database. Fig. 3a–f illustrate in greater detail the ability of the multiple regression equations to match observed data for the cases deemed acceptable for use as a proxy.

5.2. Proxy 2: looking for consistency among reported deposits

For proxy 2, we consider that the deposits reported to contain indium in the literature which make up the database might show consistent characteristics between one another. If there is consistent behaviour among those deposits which are reported, we may be able to make

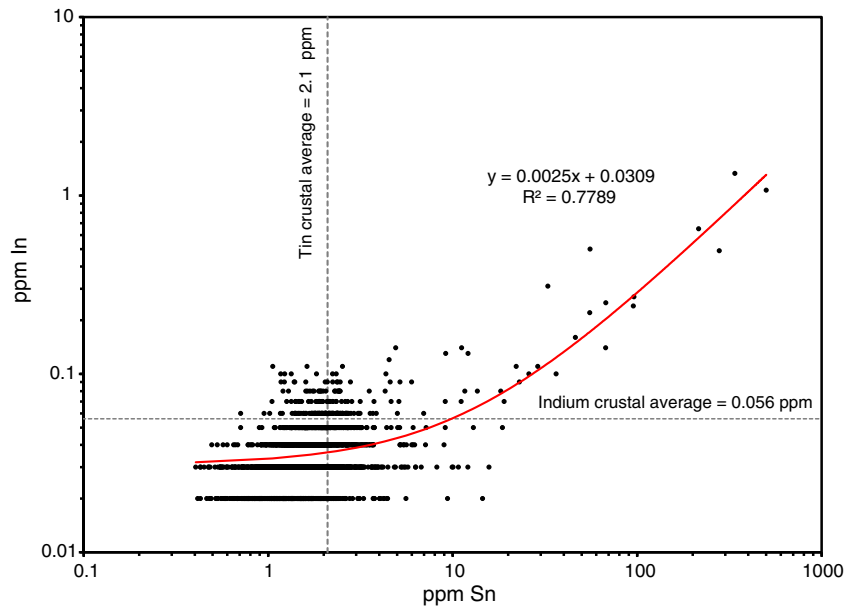


Fig. 2. Correlation between the Sn and indium concentrations within surface soil samples from Australia. Crustal average values taken from upper crust estimates in Rudnick and Gao (2014).

direct inferences for deposits where indium is not reported. The advantage of this approach is that it employs the most geologically relevant sources of data, as all data points are known to represent indium-enriched ore. In the following sections we outline three ways in which reported deposits may be analysed to infer indium grades for other deposits. A table of the deposits used for this proxy along with their resource data, geological characteristics and sources is provided in the Supplementary data.

5.2.1. Finding an optimum ratio between indium and Zn in reported deposits

The first approach we take as part of proxy 2 considers whether unreported indium grades can be determined through only Zn from reported deposits. As over 95% of indium is produced as a by-product of Zn production, consistent ratios between total indium and Zn content may be present in differing deposit types. This approach allows for the use of known production ratios to guide, and question the validity of, the ratios found in our collected deposit database. For example, it is known that currently around 60 g indium are refined for every t Zn mined globally (Werner et al., 2015), thus, taking into consideration extraction efficiencies, one would expect approximately 144 g indium/t Zn to be present in deposits contributing to global production in some way (Mudd et al., in press-a). This could be used to guide the interpretation of results obtained using this proxy.

A total of 48 indium-bearing deposits (10 classified as high quality, 21 medium quality, 17 low quality, see full data in Part III, Werner et al., 2016) were identified that contain reported values for both indium and Zn grades. For each deposit type in the reported database, we identified a value for g In/t Zn that would best produce a 1:1 estimate between calculated and reported indium content. Two primary approaches of unconstrained nonlinear optimisation (see Marthaler, 2013) were undertaken in order to optimise this value, using Goal Seek and Solver functions in Excel, with a third approach adopted as a mean. These approaches are explained with reference to the sample data for a given deposit type in Table 3.

1. *Minimised error:* In Table 3 it can be seen that when an estimate of 3 g In/t Zn is applied across these deposits, a total estimate of 18.5 t In is achieved and this entails a total of 4.5 t In of accumulated error for these three deposits. The minimised error approach determines the

value for X g In/t Zn that would reduce the accumulated error from 4.5 t In to as close to zero as possible using Excel's Solver function. In other words, a ratio is obtained such that the "absolute difference" column is set to a mathematical minimum. This however does not constrain the overall estimated content (i.e. the total of the "t In calculated" column). This estimate therefore produces greater precision per deposit, at the possible expense of decreased overall accuracy.

2. *Bulk accuracy:* For this approach, Microsoft Excel's Goalseek function is used to set a ratio between indium and Zn such that the total of the "t In calculated" column matches what is reported. For example in Table 3, it would aim to change 18.5 t In total estimated to be exactly 15 t In. The downside of this is that the degree of over- and underestimation necessary to achieve this bulk accuracy is not constrained (i.e. the "Absolute difference" column is not constrained). Thus, this estimate produces an accurate overall finding, but at the expense of decreased precision per deposit.
3. *Optimised average:* Taken as a mean value between that of the Minimised error and Bulk accuracy approaches.

The optimised estimate for g In/t Zn may then be applied to deposits of known Zn content to determine their likely indium content. The results of testing for this proxy are presented in Table 4.

It can be seen that despite conscious efforts to minimise error or achieve accurate total estimates using the reported data, it is difficult to find a ratio for indium and Zn that is consistently able to predict indium content, even when disaggregating into deposit types. This is a clear reflection of the limited reporting of indium grade in deposits reporting Zn grades. Despite the ratios being higher than the expected values around 144 g In/t Zn, they still underestimated the reported values. This highlights the considerable diversity of ratios in the reported database, and that they are, in general, particularly high. This result might however be expected, given that the reporting of these deposits in the first place is probably due to their particularly high indium enrichment. The diversity of ratios, even within a single deposit type, are highlighted in Fig. 4 which shows a poor overall correlation, suggesting that there are simply too few reported deposits containing indium for this approach to be considered viable at this stage. The results obtained when this proxy is applied globally are shown in Section 6, and the challenges associated with the use of this proxy are discussed further in Section 7.

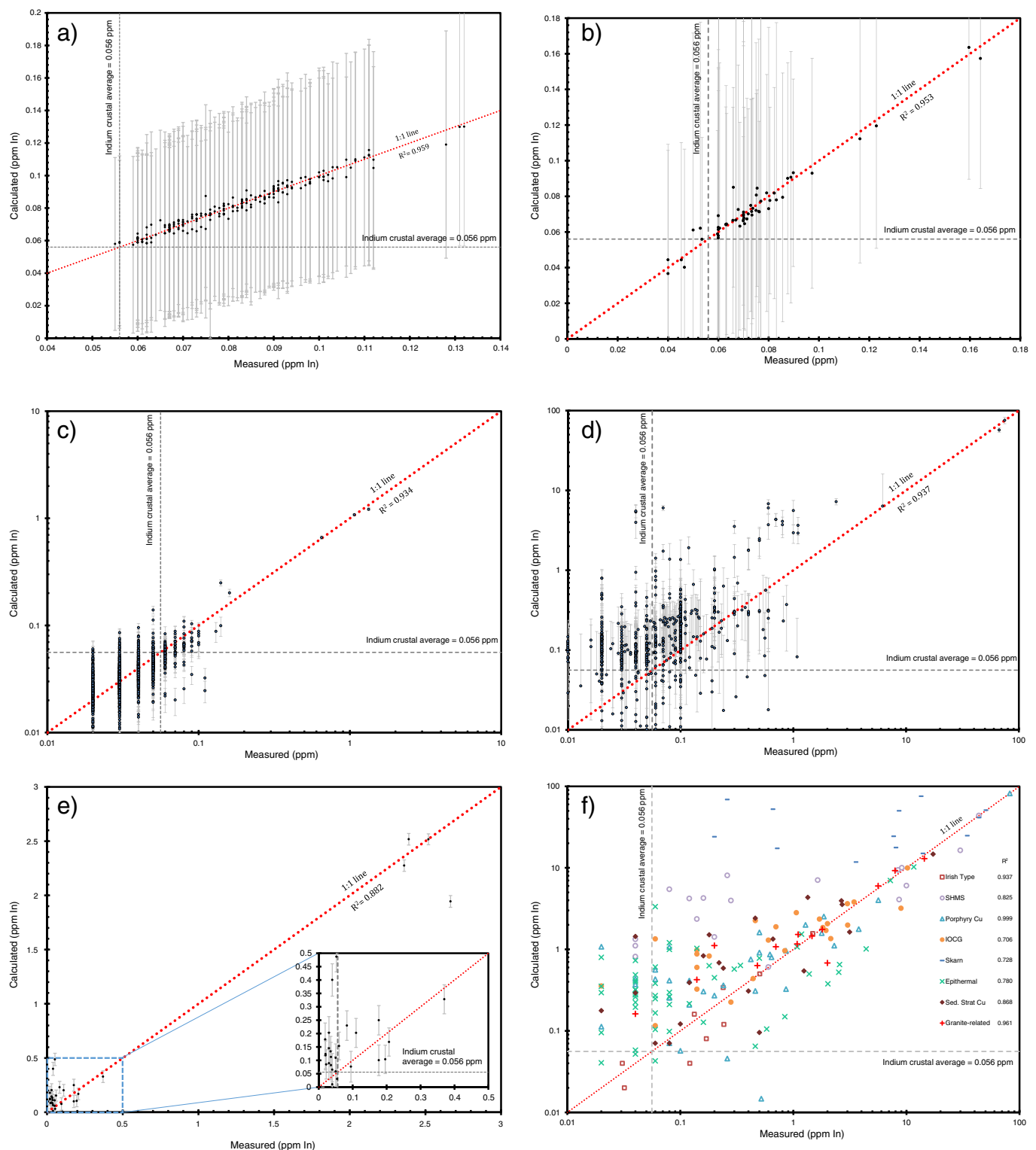


Fig. 3. Correlation between reported and calculated indium grades for the databases deemed acceptable for use as an indium proxy. Grey error bars depict a 95% confidence interval, with black markers indicating the mean value from multiple regression. Indium crustal average of 0.056 ppm obtained from estimates within the upper crust from Rudnick and Gao (2014).

- a) Earthchem.org 'SedDB'.
- b) GEOROC.
- c) Australian Geochemical Atlas.
- d) USGS Whole Rock Geochemical Database- ICPMS.
- e) NSW drillhole assay database.
- f) OSNACA Database (deposit types exhibiting regressions deemed acceptable for use as per Table 2 are shown).

Table 3

Sample table to illustrate the optimisation process.

Deposit name	Mt Zn reported	t In reported	g In/t Zn (actual ratio)	g In/t Zn (estimated ratio)	t In calculated	Absolute difference (t In)
Deposit A	1	4	4	3	3.5	0.5
Deposit B	2	5	2.5	3	6	1
Deposit C	3	6	2	3	9	3
Total		15			18.5	4.5

5.2.2. Multiple regression of Zn, Cu, Pb and Ag from reported deposits

It would be preferable that a single metal grade be sufficient to infer indium grades as this only requires the reporting of that metal, however given the poor statistical performance seen in Fig. 4, we also explore multiple regression from reported deposits, as we have done for the geochemical databases listed in Table 2. The advantage of this approach is that it can produce better statistical accuracy than using only Zn, however it requires a greater number of metals to also be reported for a deposit in order to harness this improved accuracy. In Fig. 5 we see predicted vs. reported indium grades for 28 deposits where Zn, Ag, Pb, Cu and indium grades were all reported. This achieves a modest improvement to an R^2 value of 0.556, at 95% error, however this would not meet the requirements applied to the other databases present in Table 2. In the event that over time, more deposits are reported with indium grades alongside the grades of other common commodities, this proxy may be of greater use. It may indeed apply to by-products/critical metals that are already reported more than indium (e.g. cobalt). Mainly for comparative purposes, we have still included the results of this proxy in the final analysis presented in Section 6.

5.2.3. Analysis of the mineralogy of reported deposits

The final way in which we analyse reported deposits is to consider whether the mineralogy of these deposits reveals any consistent behaviour. For this analysis, each deposit in our reported database is classified according to the minerals reported to be hosting indium, or otherwise the form of the indium mineral (see Supplementary data). Fig. 6 shows the spread of the minerals hosting indium, where reported or otherwise obtainable.

It can be seen from Fig. 6 that grades can be highly variable within particular mineral hosts, and that a greater number of reporting deposits do not reduce statistical uncertainty. Regardless, this information alone could not be used as a proxy as it is highly unlikely that a deposit without reported indium will have information on which minerals are host to it. For mineralogical information to be of use as a proxy, we

would then need to link it to other geological factors that would be more likely known about a deposit. In Fig. 7 we disaggregate the mineralogy data according to deposit types, however this only confirms that mineralogy is not a strong indicator of indium grades, at least for the reported deposits in our database. For this reason we have not considered this particular approach further in the following sections.

Given the performance of all approaches under proxy 2, we can generally conclude that it is difficult to make inferences from known deposits when the number of these deposits is severely limited by reporting. This finding assists in the interpretation of other published values. If, for example, it is known that a smaller number of deposits than are presented in our own database are used for an estimate elsewhere in the literature, we can conclude that they would not be able to encompass the geological variability necessary to be particularly accurate. The learnings and applicability of proxy 2 is discussed further in Section 7.

5.3. Proxy 3: applying published values

The final proxy outlined in this study involves the direct application of ratios or average grades found in the scientific or mining literature. Although the reviewed studies are subject to their own methodological uncertainties, the use of this proxy assists in the interpretation of results from the other two proxies by positioning them against current understandings of the metal of interest. Furthermore, it is reasonable to expect that the introduction of a greater number of possible figures from literature may otherwise assist in reducing uncertainty. An example of a value that could be used in this proxy is provided by Schwarz-Schampera (2014), who suggests that 50 g In/t Zn exist in global Zn deposits, and 10 g In/t Cu in Cu deposits. The values for Zn may be applied to the collected databases, as well as previously published deposit databases for Cu (see Mudd et al., 2013a). Although, as discussed earlier, these ratios may neglect geological variability, they still represent some understanding of global resources not otherwise captured in the first two proxies. The published average indium grades and ratios shown in Table 5 highlight how even for a metal like indium, subject to limited reporting in mineral deposits, numerous studies produce findings with potential for application to a Pb–Zn or Cu deposit database.

These data are all compatible for use with deposits in a deposit database reporting Zn or Cu grades, but should be scrutinised on their theoretical basis. It was decided that an assumed grade of 39 ppm, published by Yoshimura et al. (2013) did not have a sufficient theoretical or numerical basis to apply globally, as it was simply an average of 27 selected deposits that were already representative of high indium grades, and hence the direct application of this value as a global average would entail a clear selection bias. Similarly, the UNEP et al. (2011) value of 106 ppm indium was much higher than many deposits already reported for their indium content. Given that the act of reporting is inextricably linked to economic value and hence higher grades (see Mudd et al., in press-a), it therefore seemed unreasonable to assume a global average higher than most of the reported values and so this value was also excluded. This particular study is also based on the use of crustal abundances, and hence is methodologically flawed as we discuss in part I of this series of papers (Mudd et al., in press-a). For the ratio of 144 g In/t Zn presented in Mudd et al. (in press-a), it could be assumed that only higher grade deposits that already contribute to the indium supply chain are accounted for. The ratio of indium in non-producing deposits

Table 4

Calculated ratios of indium and Zn content by deposit type, and results using the minimised error, optimised average and bulk accuracy approaches.

	No. of sample deposits	Minimised error	Optimised average	Bulk accuracy
Ratio estimates	N	g In/t Zn	g In/t Zn	g In/t Zn
Epithermal	8	47	220	392
Granite-related	0	No data	No data	No data
Porphyry Cu	2	2040	2722	3405
Sediment-hosted stratiform Cu	0	No data	No data	No data
Sediment-hosted Pb–Zn	4	615	801	986
Skarn	7	1223	1958	2693
Tailings	2	1883	1735	1588
VMS	23	474	699	925
Results		t In	t In	t In
Target bulk estimate		39,126	39,126	39,126
Bulk estimate achieved		19,842	29,484	39,126
Final difference		–19,285	–9642	0
Accumulated error		22,881	27,393	33,227

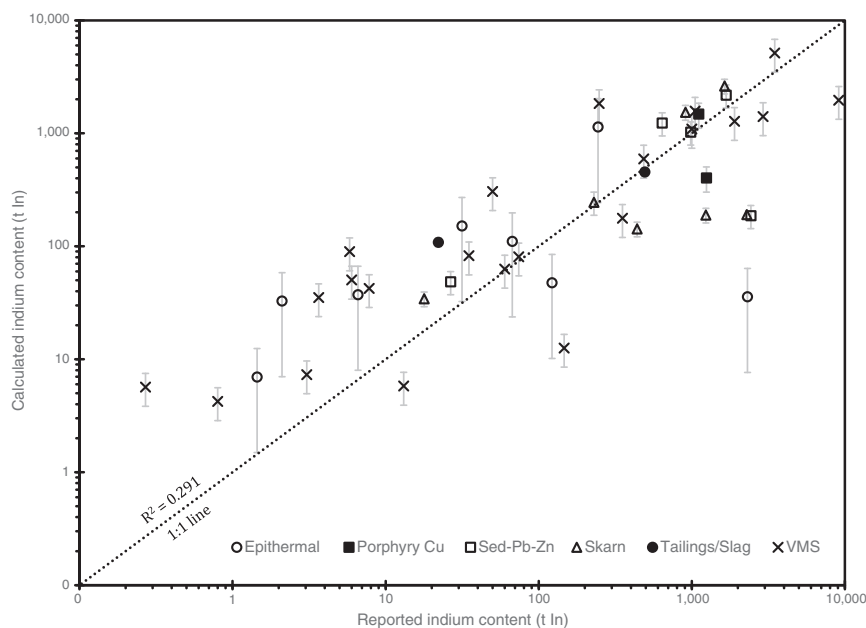


Fig. 4. Results of the optimised average approach, with error bars indicating the spread achieved through the application of the minimised error and bulk accuracy approaches, using 48 deposits of known deposit type, tonnage, and indium and Zn grades.

might therefore be assumed to be much less, potentially sitting at the same as the production ratio at 60 g In/t Zn. The ratio of 144 g In/t Zn could be weighted 0.7, reflecting the percentage of zinc smelters that are indium capable (Mikolajczak, 2009), with a lesser 60 g In/t Zn weighted 0.3 for the remaining, yielding an estimated ratio of ~118 g In/t Zn. This is shown in Table 2 as the Mudd et al. (in press-a): Modified estimate, which was also considered as a potential proxy. The ranges published by Tolcin (2014) and the European Commission (2012) were not directly included as they did not specify an average, but served as guidelines for interpretation of the other proxy estimates, as we show in the next section. The USGS and OSNACA geochemical databases are considered large and broadly representative of a diverse range of deposits. Indeed values taken from the OSNACA database are entirely based on ore characteristics, and hence the direct average grades of

indium for these database were considered valuable as additional “literature” based sources.

6. Data aggregation and analysis

6.1. Data aggregation

Up to this point, multiple data sources have been identified which may be used to estimate indium grades in mineral deposits where these grades are otherwise not reported. This is achieved either by:

- Using a combination of the reported grades of Zn, Cu, Pb, Sn, Bi, Cd, S, As, Au, Pt and Fe and deposit type information to infer deposit grades (under proxies 1 and 2)

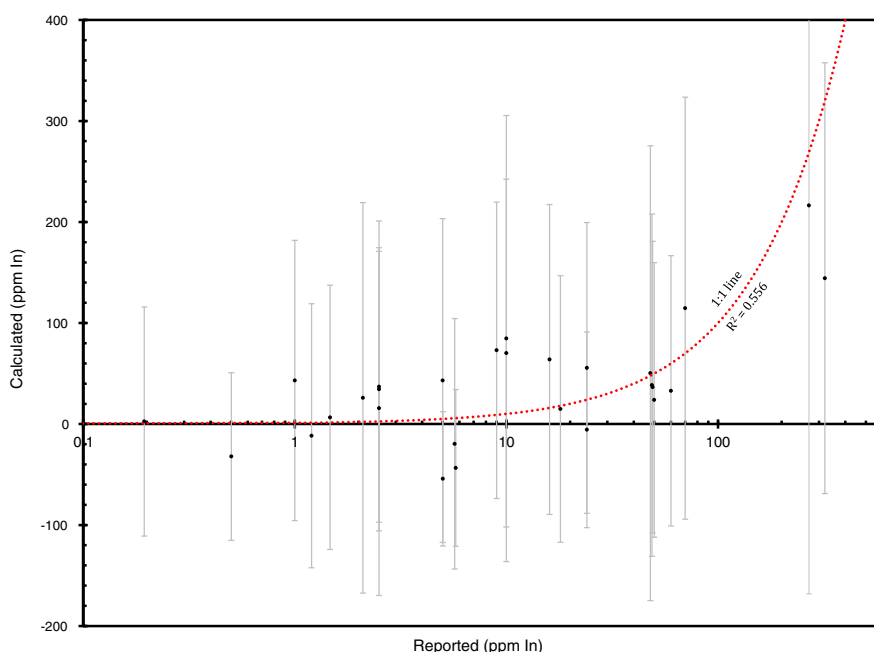


Fig. 5. Results of multiple regression using Pb, Zn, Cu and Ag grades to estimate indium, based on the reporting of 28 deposits in the literature reviewed (see Supplementary data).

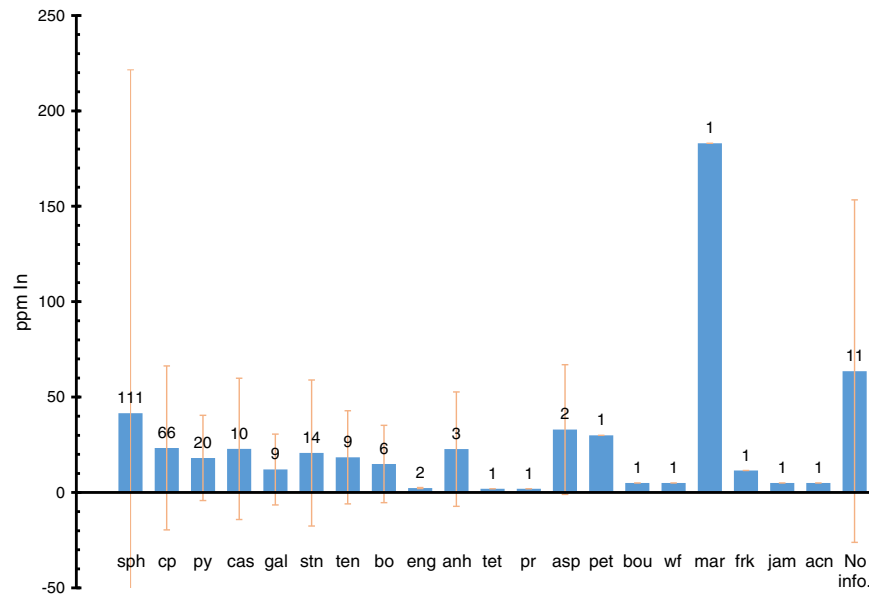


Fig. 6. Distribution of average indium grades according to which minerals are reported to host indium in the reported deposit database. One standard deviation and the number of contributing deposits is indicated. Note that indium may be reported to exist within multiple host minerals for a given deposit. sph = sphalerite, cp = chalcopyrite, py = pyrite, cas = cassiterite, gal = galena, stn = stannite, ten = tennantite, bo = bornite, eng = enargite, anh = anhydrite, tet = tetrahedrite, pr = pyrrhotite, pet = petrukite, asp = arsenopyrite, bou = boulangerite, wf = wolframite, frk = ferrokösterite, jam = jamesonite, can = acanthite, "No info." = grades reported but host minerals not known.

- Applying a fixed grade or ratio between by-product and host metals to all deposits, or differentiating by deposit type (under proxies 2 and 3).
- Assuming a fixed, constant by-product grade for all unreported deposits (under proxy 3).

Using our indium example, 26 individual approaches or estimates (13 under proxy 1, 4 under proxy 2 and 9 under proxy 3) were considered for application to a Pb–Zn deposit database with unreported indium grades (Mudd et al., *in press-b*). Some were eliminated at an earlier stage due to more obvious weaknesses, or as a result of failing preliminary statistical tests (e.g. the FOREGS geochemical database), leaving 19 actually applied to the Pb–Zn database provided in Mudd et al. (*in press-b*) as shown in Fig. 8. Note that this deposit database contains

851 entries, however 51 of these have indium contents or grades reported in the literature, and are therefore excluded from proxy analyses, leaving 800 deposits contributing to the estimates shown in Fig. 8, which would be considered in addition to what is reported. Theoretical maxima and minima, as suggested in the indium literature (European Commission, 2012; Tolcin, 2014), are also shown for reference. Each grade is listed in Fig. 8 as a weighted average grade, calculated as per:

$$\frac{\sum_{i=1}^{695} C_{i,p}}{\sum_{i=1}^{695} T_i} \quad (2)$$

where $C_{i,p}$ is the content of the by-product in a deposit, i , for a proxy, p , and T_i is the ore tonnage for that deposit. The actual global average

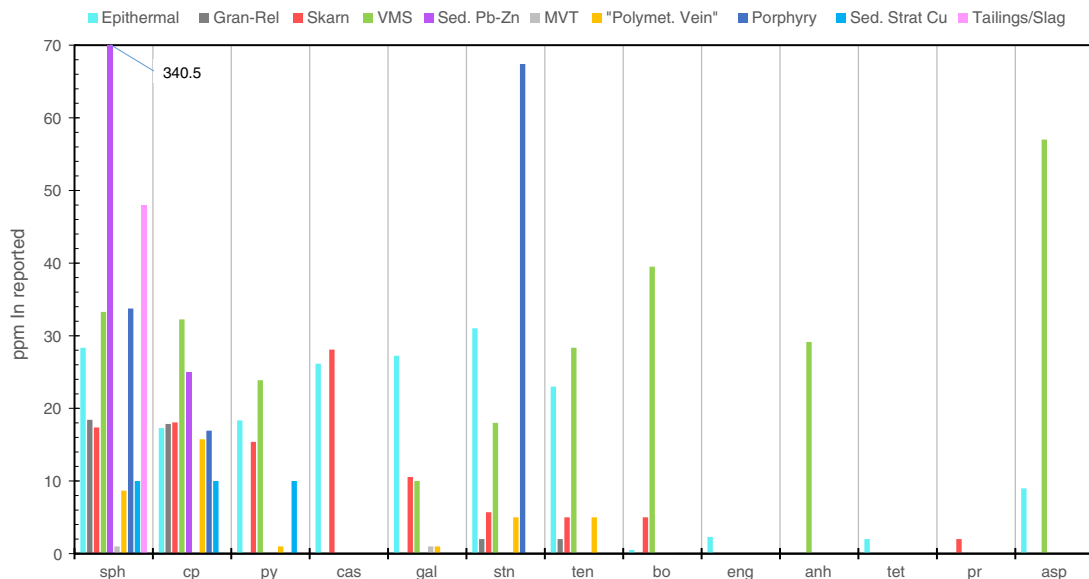


Fig. 7. Average indium grades according to host mineral and deposit type for reported deposits listed in our database. It is indicated here that host mineralogy is not a good proxy for the estimation of indium grades. Minerals are abbreviated as per Fig. 6.

Table 5
Studies estimating global average indium grades or ratios.

Global average indium grade estimate	Reference
106 ppm In	UNEP et al. (2011) – determined using factors from crustal abundance
10 ppm In in Zn ore	Liedtke and Homberg-Heumann (2012) – basis unknown.
1–50 ppm In in base metal sulphide deposits	European Commission (2012) – taken as a reference for theoretical limits
39 ppm In	Yoshimura et al. (2013) – assumed based on a weighted average of 27 selected deposits identified from Murakami and Ishihara (2013)
50 g In per t Zn in Pb–Zn deposits and 10 g In per t Cu in Cu deposits	Schwarz-Schampera (2014) – basis not specified, but assumed to have grounding in some known deposits
0.1 to 100 ppm In in Zn deposits	Tolcin (2014) – taken as a reference for theoretical limits
95 g In per t Zn in Pb–Zn deposits	Licht et al. (2015) – determined using production/efficiency estimates
144 g In per t Zn in Pb–Zn deposits	Mudd et al. (in press-a) – determined using production/efficiency estimates
118.8 g In per t Zn in Pb–Zn deposits	Mudd et al. (in press-a) – modified from the above to account for possible selection bias
6.4 ppm In – calculated average	USGS (2015b) – average of values for the whole database, to represent possible average concentrations in rock at a continental scale
6.55 ppm In – calculated average	OSNACA (Brauhart and Hagemann, 2011) – average of values for the whole database, to represent possible average concentrations across a variety of ore deposits

grade (i.e. $\frac{\sum_{i=0}^n G_{i,p}}{n}$, where $G_{i,p}$ is the indium grade for deposit i and proxy p) may also be considered, however the use of actual average grades prohibits the relative comparison of proxies as per Fig. 8, and so all values are normalised to the constant value of total tonnage in the deposit database without affecting the output resource estimates.

It can be seen that most estimates sit within the expected range suggested by Tolcin (2014) and the European Commission (2012), with Schwarz-Schampera (2014) and UNEP et al. (2011) being the exceptions. This is broadly encouraging, and the weighted average grades of most remaining proxies further only range from ~1 ppm to ~12 ppm,

which is seemingly conservative given that the highest proxy estimate other than Yoshimura et al. (2013) is still <24% of even the European Commission (2012) maximum (50 ppm). This range still results in large discrepancies for resource estimates, as the total mineral resource tonnage of ~48,519.88 Mt within the 800 deposits considered in the Pb–Zn deposit database combined with a difference in overall grade estimate of 0.1 ppm indium leads to a difference in output resource estimate of ~4852 t In. However, at the very least this approach can assist in restricting the likely range of indium grades from 0.1 to 100 ppm as per Tolcin (2014) or 1 to 50 ppm as per the European Commission (2012) to somewhere in the range of 1 to 14 ppm.

6.2. Data analysis

A direct average of the values shown in Fig. 8 is ~13.52 ppm In, which gives the “Mean” estimate of ~655,882 t In, however this seems to be strongly influenced by the outlying Yoshimura et al. (2013) and UNEP et al. (2011) estimates and it further does not account for the relative merit of individual proxies. The next proposed step is therefore to systematically analyse the strengths and weaknesses of each proxy so that their individual merits can be considered when interpreting these findings and identifying an appropriate mean. Seven criteria are considered in this study to guide the interpretation of proxies. These are listed and described below alongside an indication of how each criterion results in the differential weighting of proxies.

- Can reported grades of a deposit be used to estimate the by-product?* – The regressions in proxy 1 (Fig. 3) indicate that higher base metal grades consistently correlate with higher indium grades. A proxy should therefore be able to take one or more known metal grades into consideration when estimating by-product/critical metal grades. If one grade can be incorporated we rate this criteria “Single” and a weighting factor of 0.5 is applied. If more than one grade can be used, then we rate this criteria “Multiple” and a weighting factor of 1 is applied. A weighting factor of zero is otherwise applied for this criterion.
- Can deposit type information be considered?* – Analysis of the regressions in the OSNACA database showed that indium grades could be more accurately determined when deposits are disaggregated according to deposit type, suggesting that this is a variable which should ideally be taken into account when

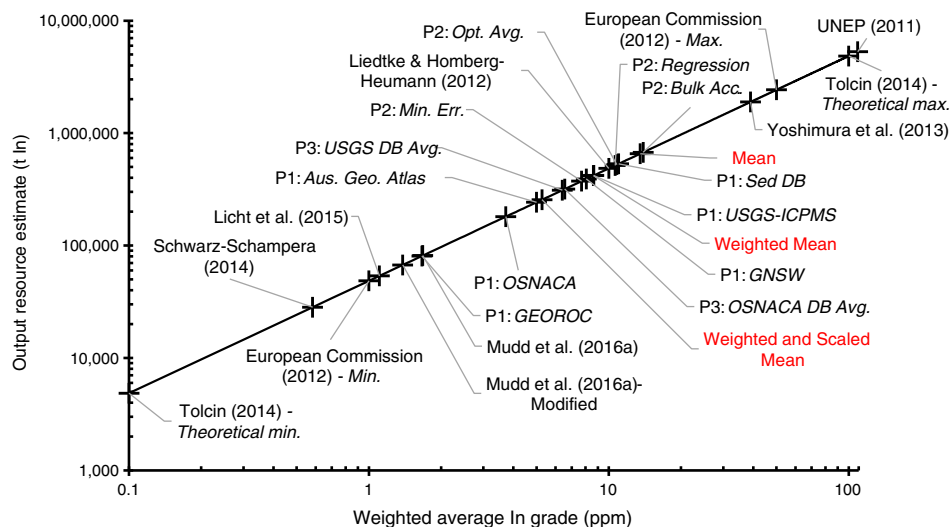


Fig. 8. Summary of grade and indium resource estimates for Pb–Zn deposits identified in Mudd et al. (in press-b). The range of 0.1–100 ppm indium suggested by Tolcin (2014) is set as the absolute bounds of possible average indium grades (termed the theoretical maximum and minimum). The European Commission (2012) publishes a range of 1–50 ppm In. All other estimates shown are used to determine the various mean values, shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6

Evaluation of different proxies.

Proxy	A: Accounts for reported metal grades	B: Accounts for different deposit types	C: Incorporates mineralogical information	D: Methodology and/or data sources are trusted and traceable	E: Data based on ore geology/known deposits	F: Rating of internal statistical accuracy	G: General comments or other considerations (not scored)	Percentage influence on “Weighted Mean”, resulting from performance against criteria A–G.
Proxy 1: multiple regression								
GEOROC	1	–	–	1	–	0.953	Regressions can accurately predict indium grades, but the uncertainty around the geological relevance of the source data is a weakness of these proxies.	6.4%
Geochemical Atlas of Australia	1	–	–	1	–	0.934		6.4%
EarthChem.org: SedDB	1	–	–	1	–	0.959		6.5%
USGS: National Geochemistry Database: Rock – ICP-MS	1	–	–	1	–	0.937		6.4%
NSW, Australia – Drillhole Assay Database	1	–	–	1	1	0.882	Regressions can accurately predict indium grades, and the source data represent behaviour within ore, however this data is not able to distinguish between individual deposit types.	10.7%
OSNACA (Brauhart and Hagemann, 2011)	1	1	–	1	1	0.742 (average)	Regressions can accurately predict indium grades, the source data represent behaviour within ore, and this data is able to distinguish between multiple deposit types.	10.3% – due to lower average R^2 values than the NSW database, despite being able to account for deposit types.
Proxy 2: analysis of reported deposits								
Optimisation of an In:Zn ratio (minimised error, accurate tonnage, optimised average)	0.5	1	–	1	1	0.291	Highly relevant and appropriate data sources (known indium-hosting deposits), but optimised values are difficult to obtain, resulting in poor statistical accuracy. Further, given that these data represent highly enriched deposits, scaling may be necessary.	8.3% × 3 for each approach
Analysis of mineralogy	–	1	–	1	1	–	While this approach is perhaps the most geologically informed, its statistical grounding is too poor to be applied as a proxy as the standard deviation for average indium grade according to host mineral and deposit type is often greater in magnitude than the mean. As mineralogical information relating to indium is scarcely available for non-reporting deposits and no clear link between host minerals and deposit type was	0% as per criterion G.

(continued on next page)

Table 6 (continued)

Proxy	A: Accounts for reported metal grades	B: Accounts for different deposit types	C: Incorporates mineralogical information	D: Methodology and/or data sources are trusted and traceable	E: Data based on ore geology/known deposits	F: Rating of internal statistical accuracy	G: General comments or other considerations (not scored)	Percentage influence on "Weighted Mean", resulting from performance against criteria A–G.
Regression based on what's reported	1	–	–	1	1	0.556	attainable, it is not possible to apply this proxy to the deposit database. While deposit type and mineralogical data are available in the database, the number of deposits with reported grades of multiple base metals required for an effective regression is limited, and hence the integration of deposit type information is restricted.	7.8%
Proxy 3: other published literature Yoshimura et al. (2013)	–	–	–	0.5	–	–	This data source is simply an average of 27 selected deposits already mined for indium in Japan. The estimate derived is correspondingly high and would entail a selection bias if applied globally.	1%
UNEP et al. (2011)	–	–	–	0.5	–	–	The methodology is clear and traceable, but based on crustal abundance which makes it problematic to refer to ore. The estimate is also much higher than would be expected even for some of the most indium-enriched deposits.	1%
Liedtke and Homberg-Heumann (2012)	–	–	–	–	–	–	The background to this estimate is unclear.	0% – due to poor ratings against every criterion.
Licht et al. (2015)	0.5	–	–	1	0.5	–	Zn ratio derived from literature, some of which represents known deposits.	3.3%
Mudd et al. (in press-a)/Mudd et al. (in press-a): Modified	0.5	–	–	1	0.5	–	Zn ratio derived from literature, some of which represents known deposits.	3.3% × 2 for each approach.
USGS (2015b)	–	–	–	1	0.5	–	Generalised dataset considered broadly representative of the deposit database and hence the average values are considered as a "literature" estimate under proxy 3. Unlike proxy 1, this approach does not involve a preliminary statistical accuracy test.	2.2%
OSNACA (Brauhardt and Hagemann, 2011)	–	–	–	1	1	–	Generalised dataset considered broadly representative of the deposit database and hence the average values are considered as a "literature" estimate under proxy 3. Unlike proxy 1, this approach does not involve a preliminary statistical accuracy test.	4.4%
Schwarz-Schampera (2014)	0.5	–	–	–	0.5	–	This reference appears to incorporate known deposits to infer a single global ratio, however the justification behind the estimate is unclear.	2.2%

considering a proxy's accuracy. This criterion is applied to determine if a proxy permits different estimates based on a deposit type classification. If deposit type information can be incorporated, a proxy is assigned a weighting of 1 against this criterion, and otherwise a weighting of zero is applied.

- C) *Can mineralogical information be considered?* – This criterion is applied to determine if a proxy recognises and accounts for differences in grades of by-products for a deposit depending on which minerals are present, and which are thought to host the by-product in question. A weighting value of 1 is applied if mineralogical information can be considered.
- D) *Are the data sources traceable and/or is the methodology clear?* – This is necessary to ensure that results are reproducible and are based on source data which are of an acceptable quality. If the methodology and data sources are both known and trusted, a weighting of 1 is applied. If there is information about one but not the other, or the methodology data sources are known but questionable, a weighting of 0.5 is applied. Where the methodology and data sources are both unclear, a weighting of 0 is applied.
- E) *Are the data geologically representative of the mineral deposits we wish to apply them to?* – This criteria is applied to establish whether or not the proxy data are based on, or are otherwise representative of, behaviour within ore, as this is the target for deposits requiring a by-product estimate in the collected database. A weighting of 1 is applied only in the case that the data are directly attributable to ore.
- F) *Are the data statistically accurate?* – There should ideally be evidence that the by-product grades predicted can match actual/reported values. This is testable for proxies based on regression. The R^2 values, as presented in Table 2, can be used to weight these proxies down by the extent of their uncertainty (i.e. if $R^2 = 0.8$, this criterion weights the proxy to 80% of its original influence). Where no evidence is provided, a proxy is weighted 0 against this criterion.
- G) *Are any other factors worth considering which might affect the validity of the data?* – This seventh criterion allows for any additional factors which are not encompassed by the first six criteria, but which still might affect the validity of the data source to be at least qualitatively considered. It is possible that factors considered in this criterion justify the exclusion of a proxy altogether.

Criteria A–C relate to a proxy's ability to allow by-product grades to be estimated for individual deposits based on the specific characteristics of these deposits. This means that the proxy permits differences between host minerals, deposit types or host metal grades to be accounted for in estimating the by-product contents of a given deposit. Criteria D–G pertain to the relevance and theoretical merit of the data sources, which must also be carefully considered when weighting the value of different proxies. Each proxy is listed in Table 6 against the criteria A–G to indicate their relative merits. The final column indicates the influence of each proxy on the weighted mean, according to their performance against the criteria. The percentage contribution is determined by:

$$\text{Weighting influence (\%)} = \frac{\sum_{i=0}^N P_i}{N \times \sum_{i=0}^N P_i} \times 100 \quad (3)$$

where P_i is the score for a proxy against criterion i , up to N criteria.

When the results for each proxy are weighted according to the final column in Table 6, a more qualitatively and quantitatively appropriate mean is determined. As shown in red in Fig. 5, this is the “Weighted Mean”, which sits at an average of 8.63 ppm In across the Pb–Zn deposit database, and results in an estimate of ~418,700 t In across these 800 deposits.

In addition to the weighting of proxies, scaling may also be used if it is believed that a proxy's results are subject to bias. In our case, the values under proxy 2, Yoshimura et al. (2013) and UNEP et al. (2011) could all be scaled, given that they have been calculated from deposits which are theoretically the most enriched, or are otherwise outside of reasonable bounds (e.g. a 100 ppm maximum as per Tolcin, 2014). The average grade estimate from potentially scalable proxies is ~36.08 ppm In, while the remaining proxies collectively average at ~5.06 ppm. Assuming that there is indeed a selection bias found for these proxies, one could scale these results down by their weight average grades versus the average of other proxies which don't require a scale, e.g. for the proxy 2 regression: 5.06/10.63 or 47.6% scale down. When all proxies are considered for possible scaling, a new global estimate of ~255,580.24 t In is obtained, at a weighted average grade of 5.27 ppm In. The weighted average grade should ideally not be applied directly to individual deposits in a database, but used to find a corresponding value for g In/t Zn that achieves this weighted average across the database. This In:Zn ratio can then be applied to individual deposits so that each one is given a separate indium grade that reflects their specific Zn enrichment. This step also permits analysis of grade differences between deposit types, or between countries, which may be of interest for future criticality assessments.

These processes of weighting and scaling allow uncertainty to be encompassed into the final estimates, and for deeper analysis and understandings of the results to arise. Considering the 800 deposits estimated via proxies, plus the 98 deposits with reported indium grade/contents in the literature (see Supplementary data), a total estimate of ~330,000 t In is achieved. Additional deposits of Cu and Sn may also be compiled and analysed to estimate additional indium resources beyond these 898 deposits, however the scope of this paper is primarily to demonstrate the possible application of the proxy method to a deposit database. Further analyses of global indium resources are provided in Part III of this series of studies (Werner et al., 2016).

7. Discussion and conclusions

7.1. Applicability

The processes described in this paper, and illustrated using indium, are not metal specific and may technically be applied to any by-

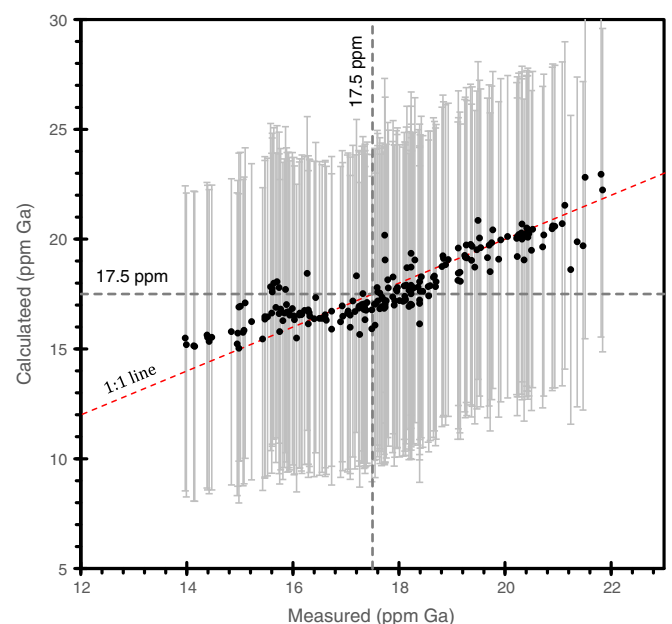


Fig. 9. Use of Sed DB data on Al and Zn to generate a Ga proxy ($R^2 = 0.76$, average error = 4%, Ga crustal average for the upper crust estimated at 17.5 ppm Ga in Rudnick and Gao, 2014).

product/critical metal for which geochemical data, production statistics and/or academic literature are available. This significantly extends the suite of metals for which deposit-by-deposit methods may be applied, an exciting prospect in terms of critical metals research. Furthermore, this method may use existing published databases of base metals, and leverage these databases to identify most, if not all, of the individual deposits from which resource assessments need to be made. For example, existing studies of Cu/Cu–Mo deposits (e.g. Mudd et al., 2013a) may be used to identify Re resources using the same approach outlined for indium here. This reduces the amount of time needed to perform detailed by-product/critical metal resource assessments. The efficiency of assessment is also assisted in that it is possible to use many of the same publicly available data sources as presented in this study to create analogous proxies for other metals. For example, using the Sed DB data, a proxy for Ga grades as a function of Zn and Al grades, its two major base metal hosts, can also be produced (Fig. 9).

Additionally, the method we present allows different proxies, and therefore different types of information sources, to be embedded. This means that the assessment of global by-product and critical metal resources need not be restricted to the types of data presented here. As geochemical and mineral deposit databases become updated, or other new information sources become available, they can be analysed and included in the framework presented here to update the result obtained without significant adjustments needed.

We have demonstrated our method for a metal subject to particularly low levels of reporting (<1% of potentially indium hosting deposits, see Part III, Werner et al., 2016). This has guided the development of the methodology as depicted in Fig. 1. However, for metals subject to an intermediate level of reporting, i.e. by-product metals with a greater market and production volumes, the body of reported data may be sufficiently representative of the geochemical behaviour of that metal, to the point that it may be used as an embedded data check for proxies. Cobalt (Co) would be an ideal candidate for this alternative approach, given the extent to which it is reported in known mineral deposits (see Mudd et al., 2013b). This alternative approach is illustrated in Fig. 10. Additional, better reported by-products like Co might also produce better results for proxy 2 than we see with indium, as proxy 2 relies on the quality of reported data to infer estimates for unreported deposits.

As a final note on applicability, it should be noted that there are various considerations that would lead to the mineral resources listed being converted to actual supply (e.g. by-product processing pathways and recovery rates), and many of these are not considered in the scope

of this work. While we have considered the ratio of by-product to host metal using some knowledge of processing behaviour in proxy 3 (discussed further in Part I, Mudd et al., *in press-a*), this is otherwise not considered in the depth that is presented elsewhere, for example by Frenzel et al. (2015). To be clear, we do not present a methodology that explicitly assesses supply potential. Our approach explicitly aims to quantify mineral resources in known deposits, and overcome a lack of code-based reporting by implementing sound approaches to by-product grade estimation.

7.2. Uncertainties and challenges

7.2.1. General and reporting

There are two types of uncertainty presented in this study. For the reported database, uncertainty is qualitatively indicated via the evaluation and classification of the reporting (i.e. “H” to “L”). This differs significantly from the quantitative uncertainty, yet both must be taken into account when interpreting the results of our methodology. While these indications of uncertainty are not directly comparable to one another, they still present a level of data provenance and reliability rarely seen in mineral resource accounting.

As highlighted by Frenzel et al. (2014), a weakness of deposit-by-deposit assessments of global resources (e.g. in Mudd and Jowitt, 2014 and adapted in this paper) is that they will always produce values below that of the true recoverable endowments, and it is further not possible to know by how much our estimate falls short. This is indeed true, as it can be challenging to identify every single deposit containing a particular commodity from a review of publicly available information (see part I, Mudd et al., *in press-a*). Similarly, there will be metals in deposits yet to be discovered that clearly cannot be accounted for using our methodology. However, it is believed that in applying proxies to quantify unreported deposits, this study has, at least to some extent, reduced the risk of this underestimation.

The amalgamation of disparate data sources, as promoted by our methodology, also naturally entails uncertainty. When it comes to using reported data to feed directly into the database, the use of tonnage from one study and the grade of another is potentially problematic as there can be little assurance of consistent modelling techniques and assumptions between the studies at the deposit level. The veins and orebodies assessed and actively mined within a broader ore field might, for example, have changed over time, without changing the name of the deposit (see Jowitt et al., 2013; Mudd and Jowitt, 2014).

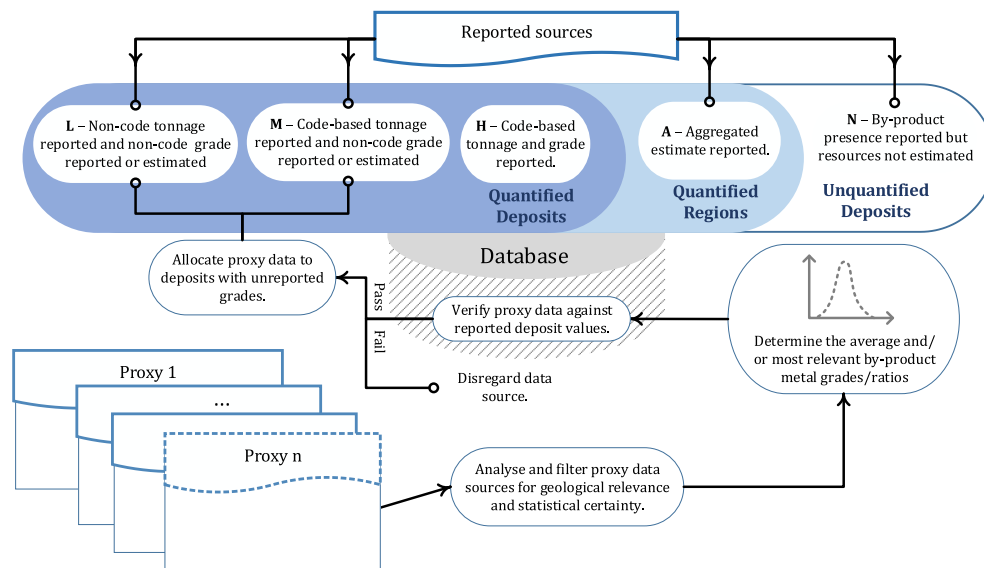


Fig. 10. Alternative approach, incorporating proxy verification against reported data.

Another possibility is that in the time between two reviewed studies, a deposit in question may have been extensively exploited, resulting in higher grade ores within the deposit being depleted. This would have the effect of our study overestimating the ore tonnage and the ore grade. The challenge of interpreting different data sources is highlighted by the Gai(skoye) deposit, Russia, which is reported to contain significant quantities of indium due to its considerable ore tonnage of 380 Mt. Possible questions about the validity of this deposit's estimate arise from the fact that the grade values found for this deposit were published by Prokin and Buslaev (1998), who at the time noted the tonnage of the deposit to simply be ">300 Mt". A later study by Herrington et al. (2005), which was ultimately used for this deposit, clarifies this to be 380 Mt, although it is still unclear whether this has been based on a rigorous exploration and assessment regime for that deposit. Whether or not the original grade estimate is still applicable to this new volume is speculative, however there was no theoretical basis for using any other value. The use of 300 Mt in this deposit would have produced an estimate 1920 t In lower, a significant margin for a single deposit (see Part III, Werner et al., 2016 and Supplementary data). This use of disparate data sources is, however, necessary given the state of reporting of many by-product resources, and is encompassed in our classification scheme for data quality (H, M, L).

Some studies that publish both ore tonnage and grade, or simply total indium content, avoid the uncertainties associated with disparate data sources, although many were still classified as low quality sources given their lack of the use of code-based resource data, and due to their propensity to be easily misinterpreted. The values published for indium by Murakami and Ishihara (2013), for example, could be misinterpreted to represent the remaining resources in a number of deposits, while some more accurately reflect the total endowment of indium in that deposit over time (i.e. the resources, reserves and cumulative production over time). Efforts need to be made where possible to ascertain whether or not the published orebody tonnage is still relevant in the database for deposits classified as L or M.

7.2.2. Proxies

7.2.2.1. Proxy 1. Geochemical databases and multiple regression allow uncertainty to be quantified and visualised, as we have shown in Fig. 3. This statistical uncertainty does not reflect other qualitative aspects such as geological relevance, and is limited in that the correlations shown apply only where all the grades incorporated into the regression are also reported for known deposits, which is not always the case. Thus in terms of statistical uncertainty, proxy 1 has both positive and negative aspects. This proxy is also subject to the nature of measurements made in each database. For example, indium measurements from surface soils in the Australian Geochemical Atlas, were found to clump in a limited set of values (Fig. 3c), which produces greater uncertainty from multiple regression than if the sample showed more variation.

The use of the proxy 1 equations inevitably results in overestimates and underestimates at the deposit level, leading these equations to suggest that for some deposits with very low base metal grades, indium grades are in fact negative. This is clearly not possible, although no deposit-level results were modified (e.g. by setting the minimum per deposit estimate to zero, or to the crustal average) so as to ensure the accuracy of proxy 1 at the global level. This could, however, be done if it could be ensured that uncertainty of global resource estimates is not considerably affected, and remains quantifiable. In the above case, no negative deposits were calculated for the Australian Geochemical Atlas, and ~3% of deposits were counted as negative by the equations of the other databases used.

7.2.2.2. Proxy 2. The development of an In/Zn ratio was considered due to the strong relationships known to exist in the processing of indium and Zn. This relationship can be used to gauge the results of using reported

grades of indium within Zn-enriched mineral deposits. Actual grades of indium and Zn were found to vary considerably between reported deposits, making it more difficult to optimise a ratio for each deposit type. The number of deposits where we could identify the type of deposit and the grades of indium and Zn were few, and this appeared to significantly limit the accuracy of the ratios obtained. Furthermore, if a base metal database contains deposit types for which no ratio can be found from reported data, this proxy cannot be applied to those deposits. This suggests that this proxy might be more appropriately applied when the state of reporting is better than it is for indium. This, however, does not exclude it from use with other by-product/critical metals. As shown in Table 4, this proxy was not able to match reported data accurately, and generally underestimated indium resources, despite being one of the higher proxies when used in the Pb–Zn database. Further development of this proxy will be needed to better establish the degree of weighting and scaling needed, and to establish better grounds for the quantification of this proxy's uncertainty. At present, one could use the ratio of H, M and L estimates contributing to the development of the by-product/base metal ratio, however it would take some further work/justification to translate this to a quantifiable weighting. Our results generally suggest that assigning fixed by-product to base metal ratios using known deposits is a highly uncertain practice, despite the common application of this approach in the literature (see Table 5).

Attempts were made to find consistency relating to the minerals reported to be host to indium among the deposits present in the reported database (see Supplementary data). However, as shown in Figs. 6 and 7, there is considerable variability of indium grades between host minerals, and increases in statistical consistency are not seen when disaggregating between deposit types. Even if a statistical link between host minerals and deposit types, or between host minerals and major commodity grades is found, it is still problematic to assume host mineralogy for deposits not reporting indium. This is quite evident from the variety of minerals present in Figs. 6 and 7, and instance of outlying cases such as Malku Khota, Bolivia, where indium is hosted by jamesonite and acanthite (see Supplementary data), but no other locations reported these minerals.

Of the approaches considered under proxy 2, the regression approach produced the best results from a statistical perspective. It is analogous to the approach of proxy 1, but is based on reported deposits, meaning it rates better than most geochemical databases against criterion E (Table 6). While this makes it highly geologically relevant, the state of reporting limits the application of this approach, and indeed a significantly lower R^2 value around 0.5 raises questions about the accuracy of grade estimates at the individual deposit level. At this stage, it would appear that endeavours to perform regressions, as well as optimise an individual by-product to host metal ratio would benefit from improved reporting, significantly more so than attempts to draw mineralogical links.

7.2.2.3. Proxy 3. This proxy involves the use of estimates derived from literature, and is possibly the most problematic in terms of determining the source and quality of estimates. The uncertainty associated with these estimates is therefore difficult to quantify, and indeed, not quantified in our indium example. Given that the results of proxies 1 and 2 both have some level of data provenance from which we can apply scrutiny, data collected under proxy 3 was consistently weighted lower. More analysis is needed to understand the sensitivity of the final results to the values used in proxy 3, and to better understand the quality and source of these data. This would result in a greater suite of sources to be incorporated, as is demonstrated by our analysis of Liedtke and Homberg-Heumann's (2012) estimate of 10 ppm In as an average estimate in Zn ore (see Table 6). While this value is consistent in comparison to the other results obtained, its basis is so unclear that it was weighted to 0% for failing to meet any of our weighting criteria.

The use of literature as a reference tool is still broadly considered a useful addition, as Fig. 8 shows that most resource estimates clumped

into a smaller fraction of the theoretical limits for indium in Pb–Zn deposits. Furthermore, from the range of values presented in proxy 3, and an understanding of their sources, one can still be reasonably sure that estimates upwards of ~15 ppm In are a likely overestimate, thus constraining our understanding of the acceptable range of average indium grades more so than the European Commission (2012) range of 1–50 ppm.

7.3. General contribution and conclusions

Detailed inventories of metal-bearing deposits can assist in strategically managing our remaining non-renewable resources. As population growth and technological advancement both accelerate, the need for these inventories will increase. Researchers in the field of economic geology are well positioned to inform society of the state of the world's metal resources, and studies have indeed emerged which enable a good understanding of primary mineral commodities (e.g. Ni and REEs: Mudd and Jowitt, 2014; Weng et al., 2014). Yet for these studies, we see a notable absence of by-products where they could be reported, e.g. Sc in REE deposits (see Weng et al., 2015), and Ga, Ge and indium in Pb–Zn deposits (Mudd et al., in press-b). This has led to urgent, yet broadly unanswered calls on the geoscientific community to respond with further data on these by-products (Herrington, 2013).

In this study, we have introduced a framework by which the global resources of any metal commodity may be estimated in such a way that is reproducible, is leveraged off of existing, publicly available data, does not require overly sophisticated modelling or software, and which explicitly overcomes the lack of reporting by mining companies to produce more detailed and defensible estimates. The uncertainties of these estimates have been discussed, and ways in which they can be qualified (through reporting classifications and multi criteria analysis) and quantified have been embedded into the methodology, which is an improvement upon many previous attempts to characterise global critical metal resources. We have identified avenues for refinement in the methodology which must be explored to further reduce these uncertainties. The application of the methodology to indium has been demonstrated, and the full inventory for indium and further analysis of indium resources is presented in Part III (Werner et al., 2016).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.oregeorev.2016.08.008>.

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