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The world's by-product and critical metal resources part III: A global assessment of indium

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ABSTRACT

Indium has considerable technological and economic value to society due to its use in solar panels and liquid crystal displays for computers, television and mobile devices. Yet, without reliable estimates of known and potentially exploitable indium resources, our ability to sustainably manage the supply of this critical metal is limited. Here, we present the results of a rigorous, deposit-by-deposit assessment of the global resources of indium using a new methodology developed for the assessment of critical metals outlined in Part II of this study (Werner et al., 2017). We establish that at least 356 kt of indium are present within 1512 known mineral deposits of varying deposit types, including VMS, skarn, epithermal and sediment-hosted Pb-Zn deposits. A total of 101 of these deposits have reported indium contents (some 76 kt of contained In) with the remaining 1411 deposits having mineralogical associations that indicate they are indium-bearing, yielding ~280 kt of contained indium. An additional 219 deposits contain known indium enrichments but have unquantifiable contents, indicating that our global resource figure of 356 kt of contained indium is therefore most certainly a minimum. A limited number of case studies also indicates that a further minimum of ~24 kt indium is present in mine wastes, a total that is undoubtedly smaller than reality given the minimal reporting of mine waste indium concentrations, and the extensive volume of historical mine wastes.

These quantities are sufficient to meet demand for indium this century, assuming current and projected levels of consumption. However, given indium's classification as a critical metal, its supply still remains a concern, and hence we have also discussed the economic viability and spatial distribution of the indium resources identified during this study to further our understanding of the geopolitical scarcity of this critical metal. Our results suggest that the global indium supply chain is fairly adaptable, primarily as the spatial distribution of indium resources deviates significantly from the current supply chains for this metal. Our study provides a stronger basis for future studies of indium criticality, provenance, supply chain dynamics, and stocks and flows in the fields of economic geology and industrial ecology.

1. Introduction

Indium (In) is a soft, silvery-white metal that is extracted from Zn, Sn and Cu mineral deposits. Since its discovery in 1863 and first presentation to the public at the 1867 World Exhibition in Paris (Schwarz-Schampera and Herzig, 2002), it has shifted from being a scientific curiosity to a technological necessity, and is used extensively today in solar panels, liquid crystal displays (LCDs) and touchscreens. It is indeed possible that you are reading this on a screen coated with indium-tin oxide (ITO). The role of In in the consumer electronics and renewable energy industries has fostered unprecedented growth in demand which is likely to continue this century (Werner et al., 2015). However, In is one of the least abundant elements on Earth (at ~56 ppb; Rudnick and Gao, 2014) and has a supply chain that is dominated by relatively few countries. This has led to its classification by multiple government and industry bodies as a critical metal (European Commission, 2014; Jowitt, 2015; Skirrow et al., 2013; Zepf et al., 2014). The significant concerns over the risks of In supply restrictions primarily relate to China's dominance of the In market and its history of imposing export constraints (see also Candelise et al., 2012). If In supply does become restricted, either by geopolitical or geological means, one or more of the following outcomes might be expected, similar to prior cases with cobalt, palladium and the rare earth elements (see Habib, 2015; Mudd et al., 2013b; Sprecher et al., 2015; Weng et al., 2015):

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1. The market price for In increases for a period of typically less than 5 years, until the market responds to adapt the supply situation, leading the price to return to its pre-disruption levels. This was seen in 2010, when Chinese export restrictions caused a tenfold spike in neodymium prices, only for them to return to their pre-disruption prices months later. It is however worth noting that In prices have fluctuated between $300 and $800 US dollars/kg in the last decade without such a noted supply restriction.
2. Technological innovation takes place to substitute and/or minimise In in its current end-uses. In a recent study, Graedel et al. (2015) developed a scale by which metals can be rated for their substitutability, where 0 is highly substitutable and 100 is completely irreplaceable. Here, In rated 60, suggesting that there would be some technical challenge in replacing In for its primary end uses, particularly without a loss in functionality/performance for those end uses.
3. In-rich concentrates from existing operations become more frequently processed at In-capable refineries, either by diversion or upgrading of existing facilities.
4. A broader diversification of the In supply chain leads to new mining projects developing in previously non-producing countries, and/or the recovery and reprocessing of In from mine wastes and end-of-life wastes increasing, with a subsequent rise of recycled stocks entering the market. Woodhouse et al. (2012) have examined the thresholds at which the supply of In for photovoltaic (PV) modules could be augmented.

Exponential growth in demand for In since the early 1970's has so far been met with limited shortages, thanks to remarkable improvements in the efficiency of production (see Fig. 1). This is in large part due to greater separation of In from Zn concentrates and adaptations made during the production of ITO, as processing residues from the ITO sputtering process that were originally considered waste are now largely recovered and contribute to nearly half of the In supplied to end users (Duan et al., 2015; Goonan, 2012). The extent to which such improvements in processing efficiency could continue to meet growing demand for In is, however, unclear. There are also uncertainties relating to the In supply chain, which is complicated by its strong dependence on Zn production (Nassar et al., 2015), and the fact that future demand for In might necessitate an oversupply of Zn and/or greater energy required for extraction than could be recovered by the renewable energy technologies dependent on In in the first place (Elshkaki and Graedel, 2015).

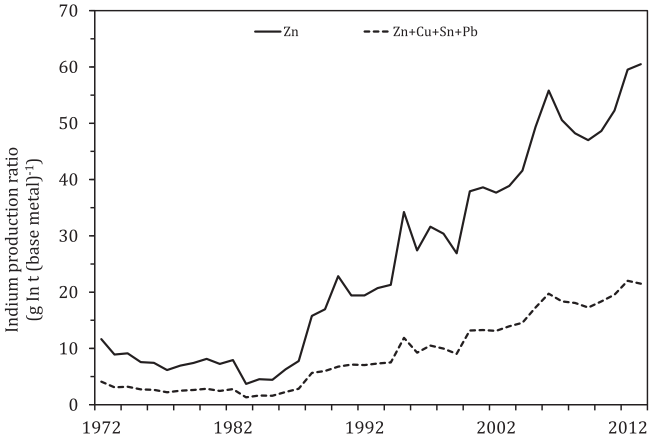

Fig. 1. Grams of refined indium per tonne of mined base metals (global), 1972–2013, showing the significant improvements in production efficiency achieved in response to increasing demand for indium. Compiled from USGS (Var.) and OCE (2014).

Policymakers and industry must therefore act strategically to ensure a sustainable supply of In for both current and future generations. This will require good knowledge of the location, quantity and quality of economically extractable primary and secondary sources of In, wherever available. However, at least in terms of primary In resources, previous studies have not produced clear or well-supported findings. For example, reports in 2007 suggested that In resources would deplete in only 10 years (Cohen, 2007), yet this study, as well as a later study by Moyer (2010) relied on misinterpretations of data originally published by the USGS (see Mudd and Jowitt, 2014). More recent studies assessing total In resources generally contradict this view, but provide little to no quantitative data to support their conclusions. This has led to enormous discrepancies in published global resource estimates (between 16 and 570 kt of contained In from studies published between 2008 and 2014, Werner et al., 2015). These discrepancies might initially suggest that defensible views on In scarcity or resource management are not possible; however, the uncertain results of past studies have remained in use as the only sources to inform policy development and mineral exploration programs. There is a need for a more authoritative assessment of In resources, and this is amplified when considering the many branches of research on In, which include, but are not restricted to: the geochemical behaviour of In (e.g. Lopez et al., 2015; Pavlova et al., 2015), its criticality (e.g. European Commission, 2014; Skirrow et al., 2013), its anthropogenic stocks and flows (e.g. Licht et al., 2015; White and Hemond, 2012; Yoshimura et al., 2013), its lifecycle impacts (e.g. Fthenakis et al., 2009; Marwede and Reller, 2014), its processing and recoverability from wastes (e.g. Alfantazi and Moskalyk, 2003; Li et al., 2006; Zimmermann and Gößling-Reisemann, 2014), and of course its scarcity (e.g. Duan et al., 2015; Weiser et al., 2015; Woodhouse et al., 2012; Zuser and Rechberger, 2011). To varying degrees, these studies require some understanding of In resources, and could produce more refined conclusions in their own respects if they could cite more robustly compiled and assessed resource data. As such, the geoscientific community has been called upon to develop detailed inventories of important commodities to address this uncertainty and assist in meeting the challenges of rising demand (Herrington, 2013).

Here, we provide a more authoritative estimation of the endowment of In in mineral deposits globally by presenting a detailed compilation and analysis of the world's In-bearing deposits, making use of CRIRSCO mineral resource reports where available. The following sections provide a summary of In mineralogy, deposit types, reported and inferred In deposits, and an analysis of the implications for future supply. The methods by which our deposit database has been compiled are described in detail in Part II of this study, which also introduces the data sources employed and explains the quantification/qualification of uncertainty. This approach has been developed in response to the uncertainties identified in Mudd et al. (2016). It is therefore recommended that Part I (Mudd et al., 2016) and Part II (Werner et al., 2017) of this study be referred to in conjunction with the following sections. A study by Mudd et al. (2017) also provides key data on global Pb-Zn resources which have been employed heavily in this study, and should also be referred to for further specific details on Pb-Zn deposits.

2. Indium mineralogy and major deposit types

2.1. Indium mineralogy

Twelve dominant In mineral phases have been identified so far (Schwarz-Schampera, 2014; Schwarz-Schampera and Herzig, 2002), although these minerals are almost always not concentrated in sufficient quantities to make them economic to extract. As such, there are currently no mines that produce or resources that host In as a primary commodity. Some minerals that contain In as a major element, most notably roquesite ($CuInS_2$), are present as microscopic or sub-microscopic inclusions within more common minerals such as chalcopyrite, cassiterite, stannite and sphalerite, enabling In to be extracted as a by-product of primary Cu, Sn and Zn production. Some chalcopyrite within Sn deposits appears to contain high concentrations of In and strong statistical correlations between In and Sn are also present in other deposits such as the epithermal Pingüino deposit in Argentina (Jovic et al., 2011; Schwarz-Schampera and Herzig, 2002). However, the most economically important source for In remains sphalerite, with over 95% of global In production derived from Zn processing pipelines and at least 80% of Chinese In sourced from sphalerite-bearing ores (Qian et al., 1998). This dominance is explained by the fact that In can be easily incorporated into the sphalerite crystal lattice by coupled substitution with Cu ($2Zn^{2+} \leftrightarrow Cu^{+} + In^{3+}$), also suggesting that higher In grades can be associated with elevated Cu concentrations in sphalerite (Cook et al., 2009, 2012). Further discussion of In enrichment characteristics and a summary of studies on In geochemistry are presented in Part II of this study (Werner et al., 2017).

2.2. Major indium deposit types

The majority of important In-associated mineral deposit types have been described in Schwarz-Schampera (2014) and Werner et al. (2015), although some of these descriptions (e.g., polymetallic vein-type deposits) provide no indication of the geological processes that formed these deposits. Clear delineations of deposit types are necessary for the purposes of classification and statistical inferences, as some resource estimation methods require knowledge of deposit type (Werner et al., 2017). We have therefore expanded on the descriptions provided in Werner et al. (2015) to produce a definitive collection of In-related deposit descriptions, all of which were used to classify the reported In deposit database presented in this paper. Each of the deposits within our databases were classified using publicly available sources. Where multiple deposit types are present (e.g. Jowitt et al., 2013) the deposit was classified according to the dominant deposit type. Additional deposit types potentially hosting In mineralisation due to the presence of sphalerite (but not necessarily reported to contain In) are described in Mudd et al. (2017).

2.2.1. Volcanic-hosted or volcanogenic massive sulphide (VHMS/VMS)

VMS deposits form from heated, hydrothermal fluids discharged from vents in submarine volcanic environments at or near to the sea floor, which then precipitate massive sulphides. They source metals from interactions between source rocks such as epidosites and modified seawater (Jowitt et al., 2012). These deposits are major sources of Zn and Cu, as over 275 VMS deposits hosting Pb-Zn mineralisation are identified in Mudd et al. (2017), and at least 31.56 Mt of contained Cu are identified for VMS deposits in Mudd et al. (2013a,b). VMS deposits are known to host a wide variety of metals that are often present at high grades, which makes them economically attractive to extract and somewhat protected from the price fluctuations of individual metals (Galley et al., 2007). They are the most common deposit type among deposits reporting In in our database, hosting grades between 1 and 320 ppm In.

2.2.2. Epithermal

Like VMS deposits, epithermal deposits can host economic quantities of a wide range of metals. These most commonly include Ag and Au, although epithermal deposits can also contain Zn, Cu, Pb, As, Sb and Sn, all of which are particularly important for In (see Simmons et al., 2005). Epithermal mineral deposits form at temperatures up to 300 °C and in shallower depths (less than 1.5 km) within subaerial hydrothermal systems, driven by magmatic heat sources commonly within volcanic arc settings (Simmons et al., 2005). They may form part of greater co-genetic epithermal–porphyry–skarn systems (e.g. Jowitt et al., 2013) and notable In-bearing examples include the epithermal polymetallic deposits of Patagonia, Argentina (Jovic et al., 2015), as exemplified by the Pingüino deposit, which hosts ~122 t In.

The pH of epithermal deposits is reflective of the oxidation state of sulphur in the ore fluids, a factor that is used to sub-classify epithermal deposits into low, intermediate and high sulphidation types (Hedenquist et al., 2000). Although all sulphidation types may host In resources, it is likely that the most important of these for our study are intermediate sulphidation type epithermal systems that host Pb and Zn mineralisation. More research is needed to better understand the links between In mineralisation and these sub-types of epithermal systems.

2.2.3. Skarn

Skarn mineral deposits form during the interaction between magmato-hydrothermal fluids derived from plutons and associated deeper magma chamber systems and (usually sedimentary) wall rocks. This formation arises by a variety of different metasomatic processes that generally occur during contact metamorphism and can take place within or adjacent to magmatic plutons (Meinert et al., 2005). While not always the case, skarns can be genetically related to porphyry and epithermal deposits within larger magmato-hydrothermal systems. They can host a wide variety of metals including Fe, Pb, Zn, Cu, Au, Ag, Bi, Te W, Sn, Mo and As, and the presence of these metals is dependent on differences in composition, oxidation state and the metallogenic affinity of the pluton (e.g. Einaudi et al., 1981). It is thought that Zn, Sn and Cu skarns are probably the most important for In mineralisation, as exemplified by the Dachang and Geiju skarns in China. However, as far as the authors are aware, more research is still required to clarify this.

2.2.4. Sediment-hosted Pb-Zn

The sediment-hosted Pb-Zn class of deposits include orebodies that are not genetically related to igneous activity, are sediment-hosted, and have Pb and/or Zn (rather than e.g., Cu) as their primary commodity (Leach et al., 2005). These deposits represent the world's most important source of Pb and Zn (Mudd et al., 2017) and are therefore of considerable interest for their In content. The two primary subsidiary classifications of sediment-hosted Pb-Zn deposits are sedimentary exhalative (SEDEX) and Mississippi Valley-type (MVT) deposits. Given that both SEDEX and MVT deposits are not directly linked to igneous activity, they typically form at lower temperatures than, for example, volcanogenic massive sulphide deposits, which are formed via magmatism/volcanism (see Leach et al., 2005). SEDEX deposits are formed via the venting of hydrothermal fluids onto the seafloor, which can also result in the replacement of existing sediments. In comparison, MVT deposits form as a result of the circulation of low temperature and high-salinity basinal or connate fluids during the diagenesis of sediments in sedimentary basins (Robb, 2004). This deposition of metals generally occurs during the deposition of the sediments that host fluid flow within MVT systems. These distinctions between SEDEX and MVT deposits can at times be subjective, leading to some disagreement for deposits which show characteristics of both types (Leach et al., 2005). In addition, sediment-hosted Pb-Zn deposits are further classified into sub-types such as Broken Hill- or Irish-type deposits, which can be difficult to classify for the purposes of mineral resource accounting as technical literature often does not contain sufficient information. As such, we categorise only between SEDEX and MVT sub-types in this study, as was also done for the mineral resource accounts presented by Mudd et al. (2013a). In terms of commodities, SEDEX and MVT deposit types are both dominated by Pb and Zn, though they can also be important sources of Ag and Cu. Additional common by-products include: As, Ba, Bi, Ge, Hg, Mn, Ni, P, Sb and Tl. As discussed in Werner et al. (2015), In demand is dominantly met by the production of In as a by-product of Zn, and our database shows that substantial known quantities of In are present in sediment-hosted Pb-Zn deposits (e.g. Malku Khota, Broken Hill and Huari Huari).

2.2.5. Granite-related

The anhydrous melting of the lower crust (e.g. during mantle plume-related underplating), the melting of igneous or sedimentary rocks during metamorphism, or extreme fractionation of mafic magmas can generate highly evolved magmas. When these magmas cool and solidify, they can form either coarse-grained igneous rocks, known as granites, or their compositionally identical fine-grained equivalents, rhyolites, after cooling and solidification. Rhyolites are either intruded near the Earth's surface or erupted. Both granites and rhyolites host In mineralisation (e.g. Andersen et al., 2014) and are known to be significant sources of by-product/companion metals, although In is reported in a limited number of granite-related deposits in our deposit database. Baal Gammon, Australia, is the only instance of a granite-related deposit with full code-based reporting of In resources, although it is likely other granite-related In mineralisation is yet to be identified or fully quantified.

2.2.6. Porphyry deposits

Porphyry deposits are large-tonnage, low- to medium-grade mineral deposits that are genetically linked with porphyry intrusive magmatism (e.g., Kirkham, 1971; Sinclair, 2007; Sillitoe, 2010). They are the world's most important source of Cu as well as being associated with significant Mo, Au, and Ag endowments (e.g. Mudd et al., 2013a,b). As mentioned in the other deposit type classifications above, porphyry deposits are often associated with other mineral deposit types that may be more important in terms of In endowments, such as epithermal, skarn, and also manto mineralization (e.g., Hedenquist et al., 1998; Sinclair, 2007; Sillitoe, 2010). Porphyry deposits are commonly associated with felsic to intermediate arc-type calc-alkaline magmatism (Sillitoe, 1972; Richards, 2003; Sinclair, 2007) and can contain a diverse range of commodities, including Cu, Mo, Au, Ag, Re, PGE, W, Sn, Bi, Zn, In, and Pb (Kirkham and Sinclair, 1995). Typically, porphyry Cu, Cu-Au, and Cu-Mo deposits are not well known for significant In endowments, primarily as these deposits generally contain low concentrations of metals like Zn and Sn that are associated with In enrichments. However, some notable examples of the porphyry-type tungsten–molybdenum subclass of deposits (exemplified by the Mount Pleasant deposit in Canada; Sinclair et al., 2006) are known to contain significant concentrations of In. These In enrichments are most likely associated with a solid solution series between roquesite and sphalerite, a process that generated In-rich sphalerite at Mount Pleasant (Sinclair et al., 2006). This in turn suggests that Zn-rich porphyry deposits may host significant amounts of In that are concentrated in magmato-hydrothermal fluids derived from the silicic intrusions associated with porphyry deposits in a similar fashion to other In-enriched magmatic or magmato-hydrothermal deposits.

2.2.7. Sediment-hosted stratiform Cu

Copper-dominated sediment-hosted stratiform mineral deposits contain thin but extensive zones of disseminated to veinlet stratiform Cu and Cu-Fe sulphide mineralization (Kirkham, 1989; Hitzman et al., 2005). These deposits range in size from giant and supergiant to small deposits (Hitzman et al., 2010), although the former have so far only been discovered in three areas: the Zambian or Katangan Copperbelt, the Kupferschiefer of central Europe, and the Kodaro-Udokan Basin of Siberia (Hitzman et al., 2005, 2010). Generally, these deposits are hosted by siliciclastic or dolomitic sediments and often occur between subaerial and marine sedimentary sequences within sedimentary basins (Hitzman et al., 2005, 2010). The In potential of these deposits remains unclear, as the only currently known instance of a sediment-hosted stratiform Cu, deposit with significant In is the Waterloo deposit in Queensland, Australia (see Supporting information), which contains an estimated 8t of In. This may be because these deposits are dominated by Cu, although Ag and Co are often present and lesser concentrations of Pb, U, Zn, Au, and PGEs have also been reported from these deposits, although commonly in subeconomic quantities (Singer, 1995; Hitzman et al., 2005). The In present within the Waterloo deposit may be a function of the Zn enriched nature of this deposit compared to typical sediment-hosted stratiform Cu deposits, suggesting that this deposit may be a hybrid between sediment-hosted Pb-Zn and sediment-hosted stratiform Cu types of mineralisation, rather than strictly a sediment-hosted stratiform Cu deposit. However, this does not mean that Zn-rich types of sediment-hosted stratiform Cu deposits are not viable targets for In exploration. Further research in this area is certainly warranted.

2.2.8. Tailings and slags

Tailings represent the bulk of the uneconomic or gangue fraction of ore that is discarded during mineral processing and are generated as high volume wastes from milling that often contain sulphide minerals that can be the source of environmental contamination when exposed to oxidation or weathering. In comparison, slags typically form during the cooling of molten solutions of oxides that form as a common by-product/waste of base metal smelting and refining. Although tailings and slags do not occur naturally, we consider these to be relevant classes of anthropogenic mineral deposit types that may be an important future resource of critical metals, including In. The metallurgical processes that produce tailings and slags are optimised for specific conditions at each facility, and hence the physical composition of slags can be highly variable. This composition may additionally change over time due to the exposure of these deposits to the above-ground environment (Lottermoser, 2014). The heavy metal content of tailings and slags is also often a cause for environmental concern, and hence most are considered wastes. If the extraction from these sources leads to net reductions in local pollutant levels and/or the offset of demand from primary production, the extraction of resources held by tailings and slags can be environmentally attractive (Hagelüken, 2014; Shen and Forssberg, 2003). The Zeehan slag resource in Tasmania, Australia (Fig. 2) is one of the very few tailings or slag sites that fully report code-based In resources. Further detail on the history of this site is provided in the Supporting information.

3. Reported indium mineral resources

3.1. Mineral resource accounting

A number of deposits reported to contain In were identified during a comprehensive review of mining company websites, technical reports, published literature, mineral resource atlases and

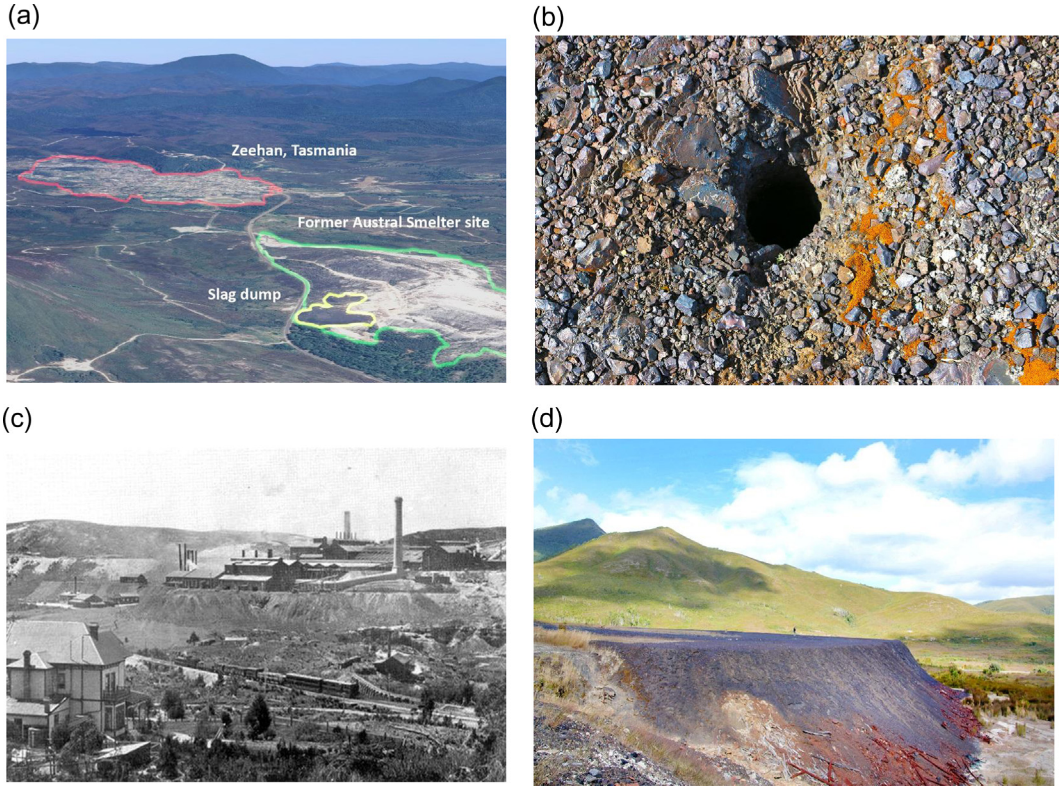

Fig. 2. a) Aerial view of Zeehan township (red), former Austral smelter site (green) and slag dump (yellow). Edited from Google Maps, 2016. b) Drill hole in the slag, reflecting the testing performed to estimate indium contents. c) View of the operating Austral Smelter site ca. 1910. Source: Twelvetrees and Ward, 1910). d) Atop the slag heaps, present da. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

other national/state mineral occurrence databases. The quality of resource data for each deposit varied considerably, meaning that it was necessary to employ a classification scheme to account for variations in data quality. This scheme essentially states that a CRIRSCO code-based classification of the grade and tonnage of a deposit means that the In content of this deposit can be considered with greater confidence than estimates otherwise found in the scientific or engineering literature (e.g. Murakami and Ishihara, 2013). Our scheme is based on (Mudd et al., 2013b; Weng et al., 2015) and is briefly summarised as follows:

- High quality (H): In grade and tonnage is reported and estimated according to CRIRSCO mineral resource reporting codes.
- Medium quality (M): A deposit's tonnage is reported using CRIRSCO mineral resource reporting codes but In grades are not reported but instead are obtained from non-code data sources such as the peer-reviewed scientific or engineering literature. A "medium-calculated", or Mc subtype of this classification is given to deposits that have tonnages reported using codes but with grades calculated using the proxy approach outlined in Werner et al. (2017).
- Low quality (L): Both In grade and ore tonnage are reported in peer-reviewed literature or other non-code study rather than using CRIRSCO mineral resource reporting. Deposits with tonnages reported without using codes and with grades calculated using the proxy approach outlined in Werner et al. (2017) are given a classification of "low-calculated", or Lc.

Of course, not all deposits that contain In have In concentrations or grades measured or reported in the literature, meaning that we have split our assessment into distinct reported and inferred databases. The reported database is presented here and the inferred database is presented in Section 6, and the compilation and analysis methods used to interpret these databases are given in Part II of this study (Werner et al., 2017).

3.2. Reported indium resource database

101 mineral deposits were identified with In reported as a commodity or potential commodity and had sufficient associated data to quantify the amount of contained In within these deposits. The fact that these deposits have reported In grades and tonnages means that they arguably represent the portion of the extractable global resource (EGR) that is most likely to be exploited in the near future (i.e. are likely to meet short term demands). The full list of these deposits along with their deposit type classifications and reported or calculated In contents are given in Table 1, with grade and tonnage data shown in Fig. 3. Data sources and notes on individual deposits are provided in the Supporting information. These data indicate that some ~9470 t of contained In are present in high quality resources, with a further ~12,912 t contained In within medium quality resources and a further ~52,066 t In present within low quality resources. These resources yield a minimum of 76,183 t of contained In, an amount that if In demand continues its linear growth as per the last 20 years (see Werner et al., 2015), would meet global demand to the year 2060.

We examined the way in which the reported In quantities are distributed between individual deposits, countries and deposit types. The majority of the In within our reported database are present in relatively few large deposits (approx. two-thirds of resources, or 48,442 t In, in the top 10 reported deposits). The largest deposit in our database is the Gaiskoye (Gai) deposit in Russia, which contains over 9000 t In. This is more than the bottom 77 deposits within our reported database combined, primarily as a result of the large size of this deposit. The major In deposits within

Table 1
The 101 deposits known to contain In that were quantifiable via the methodology outlined in Part II of this study (Werner et al., 2017) as a result of the availability of reported deposit tonnage and indium grades, or the grade of base metals from which indium grades could be inferred (for deposits rated Mc and Lc).

Country	Mine site name	Tonnage Mt	Grade g/t In	Contained t In	% Zn	% Sn	g/t Ag	g/t Au	% Pb	% Cu	Primary deposit type	Company[1]	Report Quality
Argentina	Pingüino	10.58	11.5	**122**			62.9	0.38	0.62		Epithermal	Argentex Mining Corp	H
Australia	Avebury Mine –Zeehan (Slag)	0.42	48	**20**	13.6		55		1.5		Tailings/ Slag	Intec	H
Australia	Baal Gammon	2.8	38	**106**		0.2	40			1.0	Granite-Related	Monto Minerals/Slow Peak Mining (and formerly, Kagara)	H
Australia	Conrad–King Conrad	3.1	5.7	**18**	0.6	0.2	95.4		1.3	0.2	Skarn	Malachite Resources	H
Bolivia	Malku Khota	485	5	**2431**	0.05		23.7		0.1	0.0	Sed-Pb-Zn	TriMetals Mining Corp (formerly Sth. Amer. Silver Corp)	H
Canada	Mount Pleasant (North Zone)	18.5	67.4	**1246**	0.8	0.3				0.1	Porphyry	Adex	H
Canada	Silver Range – Keg (Main Zone)	39.8	5.8	**229**	0.8	0.03	30.3		0.3	0.2	Skarn	Silver Range	H
Germany	Geyer Southwest, Saxon Ore Mountains	12.6	35	**439**	0.6	0.5					Skarn	Deutche Rohstoff AG	H
Germany	Tellerhäuser	32.2	71	**2286**	0.7	0.4					Skarn	Saxore Bergbau	H
Namibia	Namib Lead-Zinc Project	0.9	29	**27**	5.7		44.8		2.4		Sed-Pb-Zn	North River Resources	H
Peru	Ayawilca	13.3	68	**909**	5.9		14		0.2		Skarn	Tinka Resources	H
USA	West Desert (formerly Crypto)	71.1	23	**1636**	1.9					0.2	Skarn	InZinc Mining (formerly Lithic Resources)	H
Argentina	Pirquitas	33.6	2	**67**	1.5		172.1				Epithermal	Silver Standard	M
Australia	Balcooma – Polymetallic/Zinc	2.3	2.5	**6**	5.5		29.4	0.3	2	1.2	VMS	Kagara	M
Australia	Balcooma – Copper	1.2	2.5	**3**	0.9		15.6	0.1	0.4	2.7	VMS	Kagara	M
Australia	Broken Hill (Main)	33.5	50	**1675**	8.1		75.6		6.3		Sed-Pb-Zn	Perilya	M
Australia	Broken Hill (Rasp)	19.7	50	**984**	6.5		85.1		5		Sed-Pb-Zn	Toho Zinc	M
Australia	Dry River South	0.7	5	**4**	6.9		62.1	0.6	2.5	0.9	VMS	Kagara	M
Australia	Mt Chalmers	3.6	10	**36**			8	0.8		1.2	VMS	Echo Resources	M
Australia	Nightflower	0.2	47.9	**10**	2.2		193.6		4.9	0.2	VMS	Axiom Mining Ltd.	Mc
Australia	Rosebery incl South Hercules	24.8	10	**248**	10.6		121.3	1.7	5.1	0.4	VMS	MMG	M
Australia	Salt Creek	0.5	62.2	**33**	7		52	0.3		2	VMS	Venturex/Venturex Resources	Mc
Australia	Waterloo	0.8	10	**8**	10.2		48.1	1.2	1.6	1.8	Sediment-hosted stratiform Cu	Kagara	M
Bolivia	Bolivar	15.4	150	**2311**	1.1		19.5			0.8	Epithermal	Sierra Metals	M
Bolivia	Porco	2.4	52	**122**	9.2		91		0.8		Epithermal	Glencore-Xstrata	M
Bolivia	Pulacayo (Paya)	20.7	0.3	**6**	1.4		104.3		0.3		Epithermal	Comibol/Prophecy Development Corp.	Mc
Bolivia	San Vicente	6.6	1	**7**	2.6		342		0.3		Epithermal	Pan American Silver Corp.	M
Canada	Akie	68.2	0.4	**24**	5.2		9		1		Sed-Pb-Zn	Canada Zinc Metals	Mc
Canada	Brunswick 12-Bathurst	1.5	48.8	**74**	7.6		92		3	0.3	VMS	Xstrata	M
Canada	East Kemptville (Main and Baby Zones)	80.4	15.4	**1236**	0.1	0.1				0.1	Skarn	Avalon Rare Metals, Inc.	M
Canada	Horne No. 5	67.6	0.05	**3**	0.7			1.8		0.2	VMS	Falco Resources	Mc
Canada	Keno Hill – Onek	0.8	74.9	**61**	13.1		196.6	0.6	1.2		Epithermal	Alexco	Mc
Canada	Kidd Creek	38.0	50	**1900**	4.8		55.3			1.9	VMS	Xstrata	M
China	Qinghai Deerni	20.6	0.09	**2**	0.4					1.2	VMS	Zijin Mining	Mc
Czech Republic	Cinovec	28.1	1	**28**		0.4					Granite-Related	European Metals	M
Kosovo	Drazhnje	4.7	4.9	**23**	4.9		45		2.4			Lydian International	Mc
Papua New Guinea	Eastern Manus Basin – Solwara 1	2.6	57	**146**	0.7		29.6	5.8		7.7	VMS	Nautilus Minerals – PNG Gov	M
Papua New Guinea	Eastern Manus Basin – Solwara 12	0.2	57	**13**	3.6		56	3.6		7.3	VMS	Nautilus Minerals – PNG Gov	M
Peru	Cerro de Pasco	203.1	1.2	**244**	2.6		100.2		1.1	0.2	Epithermal	Volcan Compania Minera	M
Peru	Morococha	15	2.1	**32**	4.6		186.5		1.4	0.5	Epithermal	Pan American Silver Corp.	M
Peru	Santander Project	31.1	0.5	**15**	3.3		22.7		0.5	0.1	Skarn	Trevali	Mc
Portugal	Lagoa Salgada	8.4	1.5	**12**	2.6		52.9	0.8	2.7	0.3	VMS	Portex Minerals Incorporated	Mc
Portugal	Neves Corvo	193.3	18	**3480**	3.8		53		0.9	1.2	VMS	Lundin Mining	M
United Kingdom	South Crofty, East Pool and Agar Mines	3.5	0.4	**1**	0.3	0.3				0.5	Skarn	Celeste Copper	Mc
USA	Bingham Canyon/ Kennecott Copper Mine	859	0.1	**86**			1.6	0.1		0.2	Porphyry	Rio Tinto	M
USA	Santa Rita	356	0.1	**36**				0.02		0.5	Porphyry		M
Australia	Isabel	0.05	140	**7**							Granite-Related		L
Azerbaijan	Filizchay/Filizchai	95	16.9	**1605**	3.63		44.2		1.43	0.6	Sed-Pb-Zn		Lc
Bolivia	Carguaicollo	10	15	**150**							Epithermal	Private Interest	L
Bolivia	Colquiri	17.7	37	**484**							Granite-Related	Comibol	L
Bolivia	Huari Huari	3	1867	**5601**							Sed-Pb-Zn		L

Table 1 (*continued*)

Country	Mine site name	Tonnage Mt	Grade g/t In	Contained t In	% Zn	% Sn	g/t Ag	g/t Au	% Pb	% Cu	Primary deposit type	Company[1]	Report Quality
Bolivia	Potosi	140	29	**4030**							Epithermal		L
Bulgaria	Elatsite/Elacite	100	0.1	**10**							Porphyry		L
Canada	Geco/Manitouwadge	58.4	50	**2920**	3.5		50		0.2	1.9	VMS		L
Canada	Heath Steele	21.4	49.1	**1050**	10.5		40		2.2	0.5	VMS	Noranda – Falconbridge – Xstrata (Current)	L
Canada	Silver Queen (Cole Lake)	0.8	2.5	**2**	17.7		449.1	1.7	6.7		Epithermal	New Nadina Exploration	L
Canada	Silver Queen (Wrinch)	0.6	2.5	**1**	5.5		191.3	3.5	0.8	0.3	Epithermal	New Nadina Exploration	L
Canada	Sullivan-Kimberley	12.8	50	**640**	12		128.7		11.2		Sed-Pb-Zn		L
China	Dachang	75	117	**8775**							Skarn		L
China	Dulong	28	183	**5124**							Skarn		L
Czech Republic	Tisova	3.5	24.4	**87**			13.5	0.2		1	VMS	Canadian International Minerals	L
Georgia	Dambludi	1.87	26	**49**	5.31		30.1	1.9	2.7	0.8	Epithermal		Lc
Germany	Freiberg	4.7	1	**5**							Skarn		L
Germany	Freiberg (Tailings)[2]			**40**							Tailings/ Slag		L
Germany	Rammelsberg	27.2	25	**680**							Sed-Pb-Zn		L
Germany	Pöhla-Globenstein[2]			**1470**							Skarn		L
Greece	St. Philippe/Agios Philippos Mine/Kirki Mine	1.5	7.5	**11**							Epithermal		L
India	Tosham	1	2	**2**							Granite-Related	Hindustan Zinc Limited	L
Ireland	Lisheen	3.8	15.4	**58**	12.6				2.1		MVT	Vedanta Limited	Lc
Japan	Akenobe (6 locations)	17.5	50	**875**							Epithermal		L
Japan	Ashio	24.8	49	**1240**							Epithermal		L
Japan	Ikuno	17.1	64	**1094**							Epithermal		L
Japan	Kosaka	17.8	2.5	**45**							VMS		L
Japan	Omodani	0.4	5	**2**							Skarn		L
Japan	Taishu[2]			**100**							Epithermal		L
Japan	Toyoha (8 locations)	33.7	138	**4651**							Epithermal		L
Japan	Uchinotai	8	4	**32**							VMS		L
Mid-Atlantic Ridge	Broken Spur	"0.1–0.3"	1.9	**0.2**							VMS		L
Mid-Atlantic Ridge	Snake Pit (23°N)	"0.1–0.3"	29	**3**							VMS		L
Mid-Atlantic Ridge	TAG (26°N)	3.8	1.3	**5**							VMS		L
Namibia	Tsumeb (Slag Resource)	2.9	170	**493**	9				2.1		Tailings/ Slag	ZincOx Resources	L
Northeast Pacific	Axial Seamount @ Juan de Fuca Ridge	"<0.003"	7	**0.02**							VMS		L
Russia	Bakr-Tau	1.3	6	**8**	4.7			1.5	0.7	2.6	VMS		L
Russia	Degtyarsk/Degtyarskoye	130.0	0.05	**7**	1.5				0.1	1	VMS	Polymetal International Plc	Lc
Russia	Gaiskoye/Gaiskoe/Gai/Gay	380	24	**9120**	0.7		6.3	0.9	0.1	1.6	VMS	Ural Mining and Metallurgical Company (UGMK)	L
Russia	Komsomolskoye	25	2	**50**	1.8				0.2	1.6	VMS		L
Russia	Letneye/Letnye	6	1	**6**	1.2		13.7		0.6	2.8	VMS	UGMK/State Government (Venture)	L
Russia	Podolskoye/Podolskoe	80.8	6	**485**	1.1				0.1	1.7	VMS	UGMK	L
Russia	Sibaiskoye/Sibai/Sibay	100	10	**1000**	1.6				0.04	1	VMS		L
Russia	Uzelga	69.0	0.2	**13**	2.9		35.0	1.8	0.0	1.4	VMS		Lc
South Africa	Letaba CZ, Murchison Belt	1	60	**60**	9.0		33		0.04	1.5	VMS	Maranda Mining Co.	L
South Africa	Maranda J Mine, Murchison Belt	1.1	320	**352**	23.0		30		0.03	3.1	VMS		L
South Africa	Mashawa, Murchison Belt	0.05	16	**1**	12.1		25		0.03	2.1	VMS		L
South Africa	Mon Desir, Murchison Belt	0.03	9	**0.3**	27.0		5			0.4	VMS		L
South Africa	Romotshidi, Murchison Belt	0.5	70	**35**	23.6		73		0.9	1.5	VMS		L
South Africa	Solomons, Murchison Belt	0.02	24	**0.5**	0.4		5.6		0.01	3.6	VMS		L
South Korea	Ulsan	9	10	**90**							Skarn		L
Southwest Pacific	Southern Lau Basin @ Tonga Subduction Zone	2.5	40	**100**							VMS		L
Sweden	Långban	1.3	1	**1**							Skarn		L
United Kingdom	West Shropshire Orefield (England)	1.0	1	**1**							Sed-Pb-Zn		L
USA	Kingman	4.1	269.2	**1109**	13.2		236.5	9.6	12.0	0.7	Porphyry	ARS Mining	L
			Total:	**76,183**									

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[1] Where a company is not listed in this table, it signals that a company or owner of the deposit listed was unknown to the authors at the time the database was compiled.

[2] For the Taishu, Freiberg (Tailings) and Pöhla-Globenstein locations, specific grades and tonnages were unknown, as In resources were reported only as a total quantity in the literature reviewed.

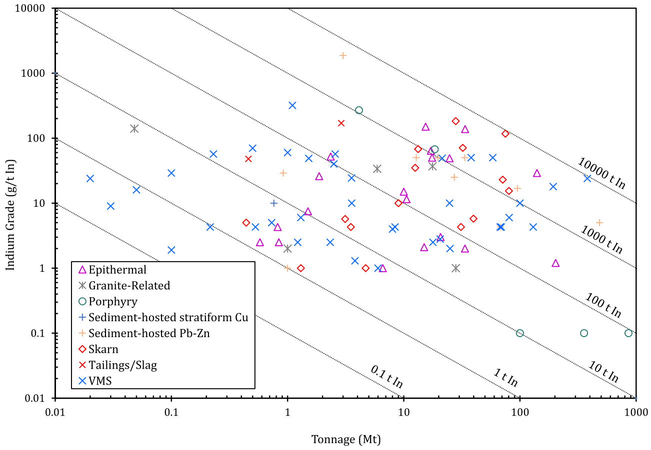

Fig. 3. Grade vs. tonnage for 101 reported indium deposits, classified according to deposit type.

our database are also located within a relatively small number of countries (Fig. 4a), with around 75% of the reported In resources in our database residing in Bolivia, China, Russia, Canada and Japan alone. This broadly reflects the state of the current In supply market (which is mostly dominated by production from China, South Korea, Canada and Japan; see later Fig. 8), although the geology of these currently producing countries is not so unique that they form the only potential sources of In. Indeed, some of the countries with major In resources in our reported database (notably Bolivia, Portugal and Australia) do not currently produce refined In, despite exporting In-laden Zn concentrates to countries such as South Korea and Japan (DoE, 2011). Such exporting but non-refining countries need only to develop domestic refining capacity in order to change the global distribution of refined In supply. This appears to be happening in Australia, as the production of refined In from local Zn concentrates is expected to soon commence following upgrades to the Risdon facility near Hobart, Tasmania (Nyrstar, 2014; Fig. 5). It is unclear whether this will affect the volume of In-laden Zn concentrates available to other countries. However, it can at least be concluded that the distribution of resources presented here may be useful to inform the distribution of future In supply, and hence can be used in more detailed future assessments of In criticality.

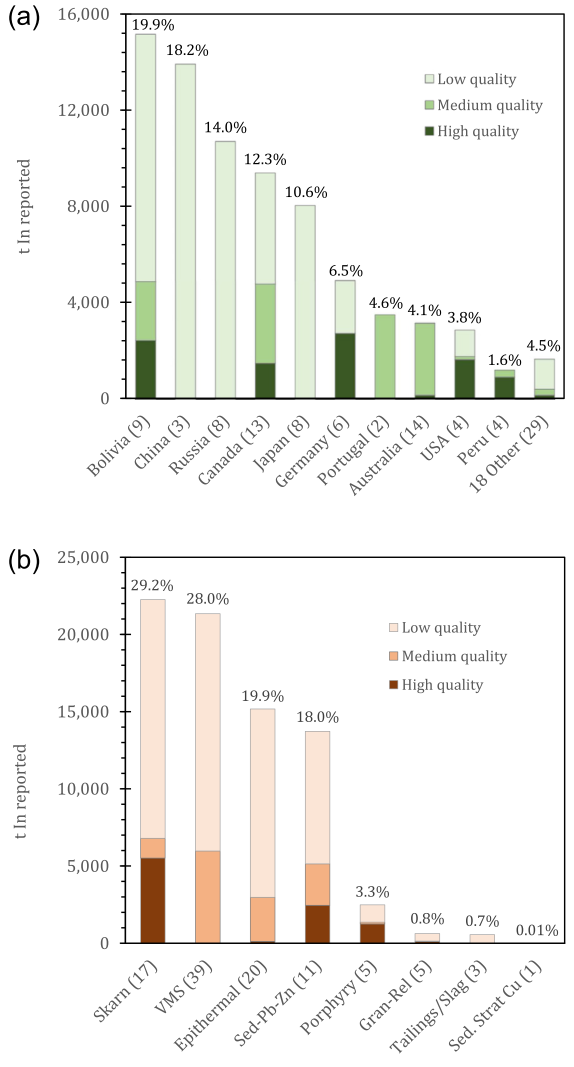

Fig. 4. Apportionment of 101 reported indium deposits according to quality of reporting by (a) country and (b) deposit type. Numbers in brackets indicate the number of reported deposits in each category.

In terms of deposit types, ~95% of reported resources reside in skarn, VMS, epithermal, and sediment-hosted Pb-Zn deposits, respectively (Fig. 4b), with the remainder mostly present in porphyry and granite-related deposits, or reported mine wastes. With the bulk of reported In present in relatively few deposit types, it would seem that a limited number of process configurations need to be outlined to enhance global In production. VMS deposits contain a large amount of In within our database, although all of these deposits have only medium or low classifications, meaning that there is less certainty that these VMS deposits actually represent the most economically viable source of In. Skarn deposits host the greatest amount of In in deposits with high quality resource reporting, suggesting that they currently represent the most economically viable processing pathway for In, although research into In mineralogy and processing is ongoing (e.g. Lopez et al., 2015; Pavlova et al., 2015).

Changes in the quality of reporting (as per Section 3.1) of In resources between countries is also evident and is shown by the shading in Fig. 4a. The highest quality reporting of In is within deposits in Bolivia, Canada, Australia, the USA and Peru, although less than one third of our reported database is associated with deposits classified using CRIRSCO mineral resource reporting codes and with code-compliant In grades. Some 12% of In resources within our database are from high quality data sources, with a further 16.9% from medium quality sources and the remaining majority (68.3%) from low quality reporting, a clear reflection of In's perception as a lower value by-product (Mudd et al., 2016).

An additional 203 deposits within our database are known to contain In but do not have quantified In grades or tonnages; these deposits are listed in the Supporting information alongside data sources and geological classifications where known. Some 45 of these deposits have reported In grades but no reported total resources, primarily as these deposits have no recently reported tonnage information. Deposits with CRIRSCO compliant tonnages and Pb and Zn grades that are known to contain In but without publicly reported In grades had In grades estimated using the proxy methods outlined in Part II of this study (Werner et al., 2017). These deposits were assigned a ratio of ~465 g In/t Zn, reflecting the weighted and scaled mean ratio between In and Zn determined by Werner et al. (2017). This yielded some, ~191 t In classified as Mc and ~1732 t In as Lc in the reported database, with a further case for the Eagle deposit in Canada having an identified resource tonnage but with insufficient base metal grade data to enable the calculation of an inferred In grade using this proxy approach.

Fig. 5. Nyrstar's Risdon facility near Hobart, Tasmania, Australia. The likely location of Australia's first refined indium production.

Sixteen other Japanese deposits listed by Ishihara et al. (2006) were reported to contain "less than 500 t In", but could not be more accurately quantified; as such, these deposits are not included within our database but we note that they could technically contribute up to 8000 t more In, highlighting that our reported database most certainly represents a minimum estimate of known global In resources.

4. Inferred indium within Pb-Zn and Cu deposits

4.1. Unreported indium resources

Not all In-bearing mineral deposits have In contents that are reported in the technical literature or within mineral occurrence databases. This meant that separate databases of deposits hosting minerals likely to contain In were also necessary to consider. Here, we used a recently compiled database of global Pb-Zn resources containing 851 deposits with quantified Pb-Zn resources (see Mudd et al., 2017 for the full database); some 51 of these deposits have known In concentrations that are already accounted for in our reported database, and hence are not discussed further. The remaining 800 deposits with unknown In concentrations had In resources assigned to them using the estimation proxy approach outlined in Part II (Werner et al., 2017). We justify this estimation approach by the fact that these deposits almost certainly contain some In as a result of the presence of significant (i.e. potentially economic) amounts of sphalerite, which is the source of most (>95%) of In currently extracted (Schwarz-Schampera, 2014). Code-based tonnages are reported for 518 deposits, tailings or stockpiles in this database (resulting in a "medium-calculated" quality estimate with proxies applied), and the remaining 282 have non-code tonnages (resulting in a "low-calculated" quality estimate with proxies applied). The amount of In present in these deposits was estimated using weighted and scaled means involving nineteen different estimates (more details of this approach are given in Werner et al., 2017), corresponding to an average of 5.27 ppm In within Pb-Zn deposits and a ratio of 465.3 g In/t Zn within each deposit. Only 775 deposits in this database contained reported quantities of Zn, meaning that 25 deposits were assumed to not contain any In. The remaining deposits have grades and tonnages shown in Fig. 6.

Another recently compiled database of global Cu resources containing 730 deposits with quantified Cu resources (Mudd et al., 2013a), 611 of which were not present within the other two databases, was also analysed during this study. These deposits likely contain In as they contain significant amounts of chalcopyrite, although the In within these deposits is almost certainly present in lower concentrations than in the Pb-Zn deposits described above (Cook et al., 2011). Here, we use a simpler approach to estimate In quantities within these Cu resources given that less than 5% of In supply is derived as a by-product of Cu and Sn processing combined and research linking Cu and In grades is limited. We apply a single proxy ratio of 10 g In/t Cu as per Schwarz-Schampera (2014), resulting in an average grade of 0.05 ppm In for these deposits. Notably, this is just below the crustal average for In, suggesting that this estimate is highly conservative. In the absence of any other published estimates for Cu deposits, we have not applied any other values. A plot of In grade vs. tonnage for these deposits is also given in Fig. 7, ultimately reflecting the distribution of Cu

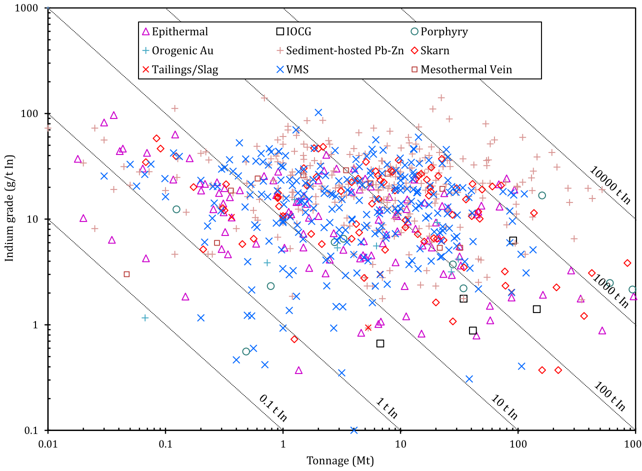

Fig. 6. Inferred indium grade vs. tonnage for 775 Pb-Zn deposits, classified according to deposit type.

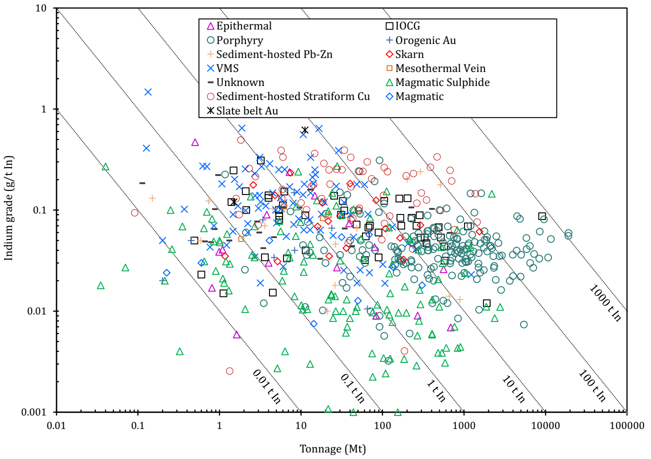

Fig. 7. Inferred indium grade vs. tonnage for 611 Cu deposits, classified according to deposit type.

grades within these deposits. It is therefore similar to Fig. 2 in Mudd et al. (2013a).

5. A summary of global indium resources and their distribution

5.1. Combining each database

The first database of 101 deposits identified during this study have In contents that are explicitly reported in one or more literature sources and yield some 76 kt of contained In. Although less than one third of this is hosted by medium and high quality resources (see Fig. 2), this value represents the most detailed assessment of known In-bearing deposits to date. The secondary databases of 800 Pb-Zn and 611 Cu deposits that have inferred In contents as they contain sphalerite are estimated to contain ~263 kt In and ~17 kt In, respectively. This results in a total of 1,1512 known deposits containing some 356 kt of In, representing the current best estimate of the world's In resources in known mineral deposits. Fig. 8 shows how these quantities are apportioned between countries within each database and compares our data to the quantities and distribution of In supply for the year 2015 (see USGS, 2016). Fig. 9 shows a map of the location of the majority of these deposits globally, organised by database. These resources, if entirely turned into reserves and production, are sufficient to meet continuing growth in consumption well into the next century, particularly as significant unreported volumes of In are probably present within known global Pb-Zn deposits. However, enabling this business as usual growth in In consumption will depend on a number of social, technical and geopolitical factors that are distinct from the sheer quantities of In that are available and are already currently known. Additionally, the apportionment of these resources according to deposit type and source database is shown in Fig. 10a, along with a more detailed country breakdown in Fig. 10b. This highlights the potential contributions made by different deposit types beyond what is indicated from the reported database alone, as shown in Fig. 4 (b).

The high criticality of In is strongly influenced by its supply distribution, although Fig. 8 indicates that any restriction of exports from countries like China could be counteracted by other non-producing countries like Bolivia and Australia, who are currently well positioned to enter the market and mitigate the impacts of a supply restriction. This, however, would require investment into In refining capacity in these countries. We have also shown the distribution of known In refining capacity (as per European Commission, 2012) for the year 2010 in Fig. 8. At the time of writing, we are aware of some efforts to establish new In refining capacity at Nyrstar's Risdon facility in Tasmania, Australia (Nyrstar, 2014), which is not shown in Fig. 8.

5.2. Other aggregated estimates

Some resource estimates are not applicable to individual deposits but instead have been compiled for certain regions and here are termed 'aggregate' estimates. It is not possible to directly disaggregate these estimates and apportion these resources to individual deposits in our database, but we include these studies to ensure the completeness of our research. The first notable example is from Zheng (2011), who estimated Chinese In reserves, rather than resources, to be ~12,000 t In in 2011. This is important as China does not report In resources by public or code-based reporting, meaning that Chinese In resources are almost certainly under-represented within our database, especially as China currently dominates global In supply. Our reported resource database contains 13,901 t In within Chinese resources, suggesting that the available data yield a significant underestimation as, in theory, the volume of resources would be considerably larger than that of the reserves reported by Zheng (2011), particularly if the unreported resources are classified to be inclusive of reserves. It is generally difficult to determine the extent to which these resources have been underestimated, however the resources as reported for our database in Table 1 are 4.35 times larger than reserves on average, so from this we may roughly approximate Chinese resources to be in the order of ~52 kt In. Alternatively, we could consider that China's total Zn resources are in the order of 115.7 Mt Zn (as reported in Min et al., 2012), and apply a ratio of ~465 g In/t Zn as per Werner et al. (2017), yielding a similar estimate of ~53.8 kt In.

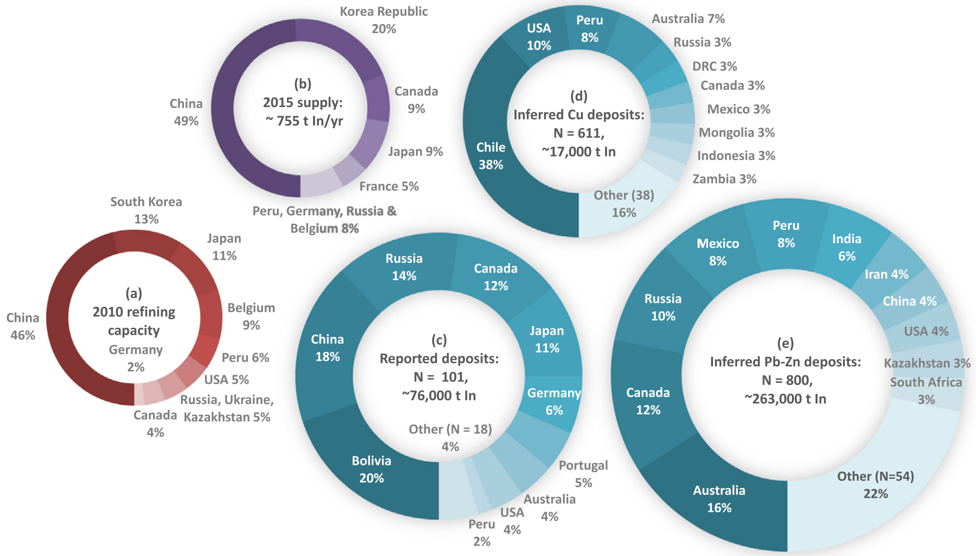

Fig. 8. Country breakdown of (a) refining capacity for indium in 2010 Source: European Commission, 2012), (b) the supply of refined indium in 2015 (Source: USGS, 2016), (c) indium in deposits explicitly reported for their indium content, (d) indium in deposits with inferred content due to their Cu mineralogy, and (e) indium in deposits with inferred content due to their Zn mineralogy, with totals indicate.

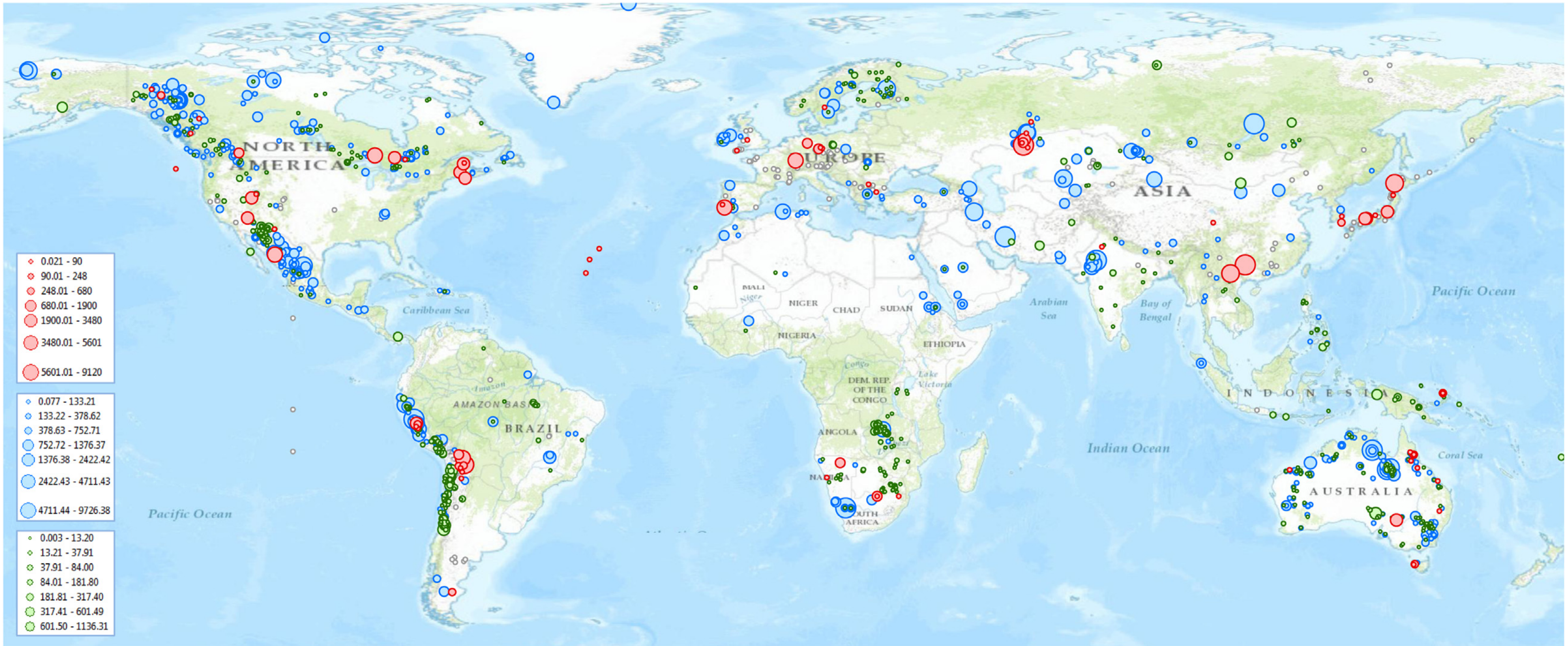

Fig. 9. Global map of indium in reported and quantified (red, N = 101), reported but unquantified (white, N = 219), and inferred Pb-Zn (blue, N = 591) and Cu (green, N = 576) deposits. Quantities depicted in the legend are in t In. Only deposits whose coordinates could be determined at the time of compilation are shown. Location data for deposits are sources from the Australian Mines Atlas, Mindat.org and otherwise estimated from site descriptions or individual site technical reported and company websites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

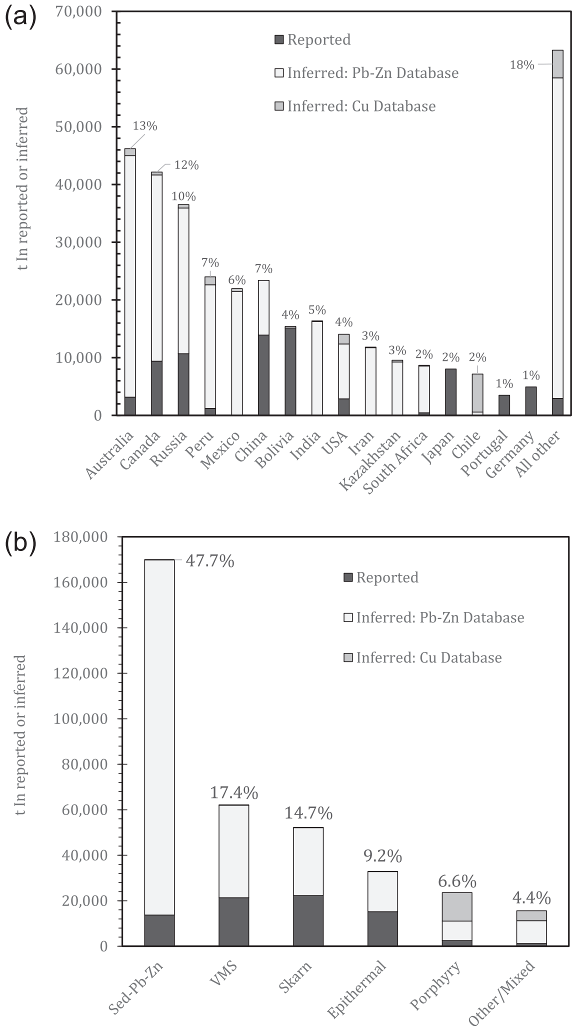

Fig. 10. Distribution of reported and inferred indium resources by (a) major deposit type classification and (b) country, indicating contributions from different deposit databases. Numbers in brackets indicate the number of deposits.

Another aggregate estimate is provided by the EU ProMine database, which was used to identify In as a commodity in multiple European deposits (see INSPIRE, 2011). A summary report for this database indicates that 630 t In resources (i.e., potentially economic for future extraction) are currently present in European deposits, although we cannot identify the individual deposits hosting these quantities. The four deposits within our database that are also listed in the EU ProMine database are reported to contain 8 tonnes of In, suggesting that other European deposits may contain a further 622 t In.

Previous research (e.g. Werner et al., 2015) has also indicated that the processing of In throughout the 20th century has meant that the amount of In in mine wastes could be in the same order of magnitude as that of unexploited mineralisation, although the former may be significantly more difficult to process than the latter (see Mudd et al., 2016). This means that a final aggregate estimate of at least 20,000 t In is present in production wastes derived from Zn processing between 1972 and 2012, in addition to the 3900 t In present in the tailings associated with two Canadian mines (Heath Steele and Brunswick 6–12; Werner et al., 2015). UNEP (2010) otherwise note that there are virtually no estimates of the stocks of any metals in tailings at national or global scales; this is discussed further in Section 6.3. The addition of these aggregate quantities, including 622 t In for the EU ProMine database, leads to a total of ~378,498 t contained In within currently known resources.

5.3. Economic viability and future processing

During this study, we conducted a review of cases where both mineralised material and concentrate In grades were published (see Supporting information) to further our understanding of the economic viability of the In resources identified. These data indicate that In is on average enriched by a factor of 7 between ore and concentrates, although this is dependent on the processing route. This enabled a rough estimation of the concentrate grades of the deposits in our database which, when combined with location data for these deposits, indicates the location of deposits with higher concentrate grades that are more likely to contribute to future In supply (Fig. 11). This is supported by the inclusions of layers indicating the location of known Zn refineries and smelters and countries reported to produce refined In (as per Tolcin, 2014). We further examine the concepts of economic viability through a breakdown of deposit monetary value in Section 6.4.

6. Discussion

6.1. Interpretation of results

The minimum of 76 kt reported contained In and 263 kt contained inferred In in known mineral deposits quantitatively indicates that the In present in known deposits is sufficient to meet the long term demand for this critical metal. More specifically, current consumption of approximately 800 t In/yr may increase to >4000 t In/yr by the beginning of the next century, conservatively assuming a linear growth trend as observed in the last 20 years (see Werner et al., 2015). Assuming no peaks in production and no contribution to global In supply from recycling indicates that deposits with known In contents (76 kt In) could meet this increase in demand to the year 2060. Furthermore, including inferred In resources (281 kt In from the Pb-Zn and Cu databases) means that this increase in demand could be met well into the next century. Of course, the quantities presented in our database must be economically extractable and then processed to a refined product for such an evaluation to be true, and processing would entail inevitable losses of In along the way. Nonetheless, we may conclude that sheer resource quantities will not be a major limitation to the supply of In to the market in the short to medium term. This somewhat contrasts with the results of modelling by Sverdrup and Ragnarsdóttir (2014), who estimated an In production peak in 2020–2045, although they used a very modest resource estimate of approximately 58 kt In.

Hotspots for reported In resources are located in Bolivia, Russia, China, Canada and Japan (Fig. 8). The fact that these deposits have been identified as having elevated In concentrations also indicates that they are worthy of additional study, given their potential role in meeting In demand over the coming decades. Hotspots for In-bearing Pb-Zn deposits where In is not reported are also present in Peru, Canada, Australia, Kazakhstan and Mexico. In addition, the fact that this study only assessed deposits primarily noted for their Zn and Cu mineralogy means that there are likely other deposits (notably Sn deposits) that could also contain significant amounts of In that could be inferred using the methodologies outlined in Werner et al. (2017). These deposits are, however, less likely to form a part of the In supply chain unless drastic pricing changes were observed, and/or advancements in the processing of In from Sn production pipelines take place. Changes in pricing may be triggered by imposed export restrictions from major producing countries such as China, changes in stockpiling behaviour,

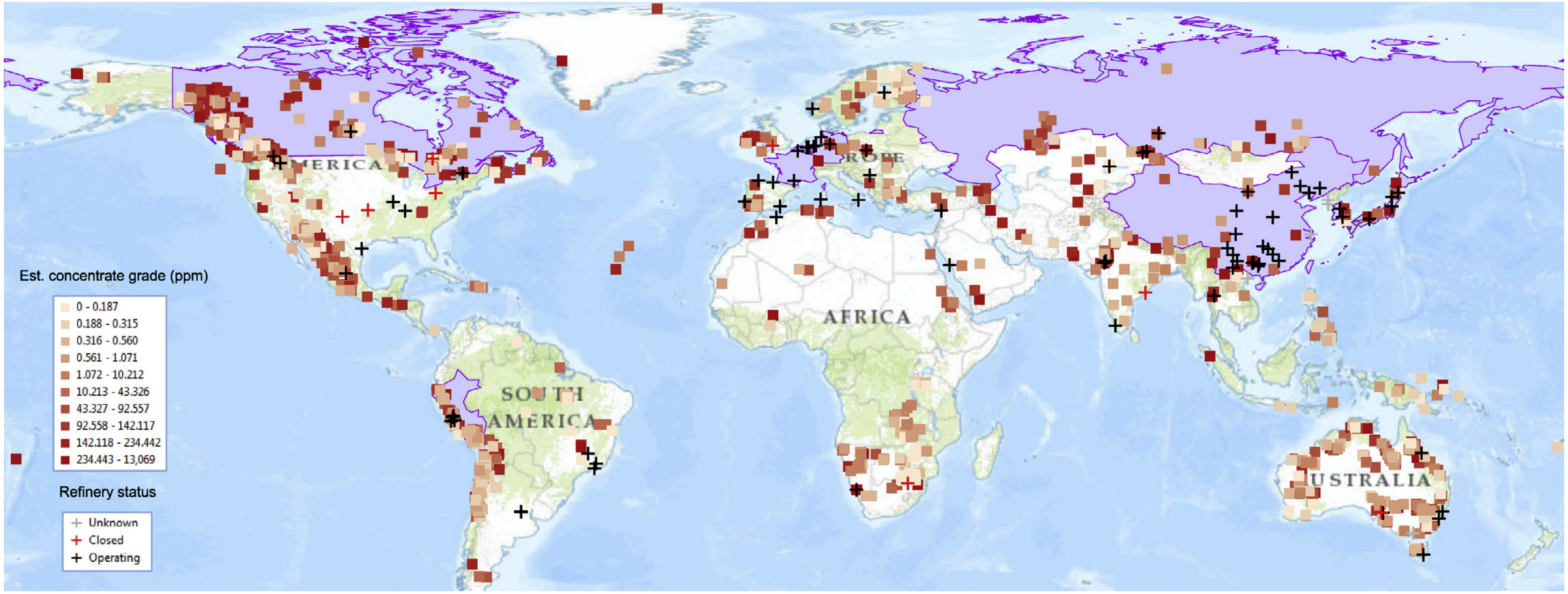

Fig. 11. Estimated concentrate grades of 1268 deposits from all deposit databases used in this study with reported or inferred indium grades and identified location data. Indicates the possibility for currently non-producing deposits to enter the market for indium in future. Countries currently producing refined indium are outlined in purple, with the location of known Zn smelters and refineries also indicated. Location data for deposits are sourced from the Australian Mines Atlas, Mindat.org and otherwise estimated from site descriptions or individual site technical reported and company websites. Zinc refinery status and locations obtained from the SNL Mining and Metal Database. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

broader trends in demand for In-containing products and the technological development of substitutes, which have historically contributed to high volatility in In prices (USGS, 2016).

In terms of deposit types, the distribution of resources in the reported database suggested VMS, skarn, sediment-hosted Pb-Zn and epithermal deposit types to be the major hosts in relatively equal terms. However, it was shown in Fig. 10 that the sediment-hosted Pb-Zn is the by far the dominant deposit type, host to roughly the equivalent of VMS, skarn, epithermal and porphyry deposit types combined when inferred In resources are included. This is primarily due to the amount of Zn in sediment-hosted Pb-Zn deposits in the Pb-Zn deposit database of Mudd et al. (2017), and the introduction of porphyry deposits as a major contributor to In resources comes as a direct result of the amount of Cu reported in porphyry deposits.

The identification of an additional 219 deposits with known In enrichments but with total In contents that could not be quantified further highlights that our findings are not representative of the true quantities present in known deposits but instead represent a minimum value. The effect of these additional deposits on resource estimates is difficult to determine, as although they are numerous, their lack of reporting suggests they have lesser economic value than more well characterised deposits. Paradoxically, some of these deposits have very high reported grades, including the Laochang and Qibaoshan deposits in China that have In grades of 179 and 253 ppm, respectively (see Schwarz-Schampera and Herzig, 2002 and Ye et al., 2011). However, these deposits have unknown resource tonnages that most likely reflect a lack of reporting rather than a lack of In resources within these deposits. The majority of these reported but unquantified deposits were identified in Europe, with lower numbers of deposits in China, the United States and Japan (Fig. 9). This is largely a result of the EU ProMine database, which was useful for cataloguing the presence of In in many locations throughout Europe, however quality resource data were not available for these deposits, and not reported within the database itself. Further, many represent abandoned sites that are unlikely to be extracted.

Our study has made use of a number of data sources of varying degrees of quality in order to build a cohesive view of the state of global In resources. This task was hindered by the mostly limited reporting of In in economic Pb-Zn, Cu and Sn deposits (Fig. 3), which is reflective of the state of reporting of many other critical metals (Mudd et al., 2016). Our results suggest that increased reporting of critical metals would assist in carrying out similar studies in future, providing significant value not only within the field of industrial ecology and in the development of future critical metals policy but also to mining companies who may consider targeting these critical metals.

6.2. Indium deportment and supply potential

While a comprehensive assessment of In supply potential from the deposits in our database is outside the scope of this paper, it is possible to make some inferences. Notably, the comparisons in Fig. 8 indicate strong deviations between the distribution of In resources and the current In supply chain, indicating the capacity to adapt to meet any challenges posed by In supply restrictions via conventional pipelines. This is an important finding in terms of future ratings of In criticality, as the development of new In processing capabilities in countries like Australia and Bolivia could seemingly address any deficits in future In production. However, the effect of increasing production in currently non-producing countries may be dampened as the Zn concentrates exported from these countries already have an important role in the In supply chain. For example, the US Government noted in 2011 that an increase in Japanese and South Korean importation of Zn concentrates from Australia could increase their own refined In production (DoE, 2011).

To learn more about the economic recovery of deposits in countries not currently producing refined In, it is necessary to consider the deportment of In to various mineral concentrates. Unfortunately however, information on the metallurgical processing of In is scarce, as this information is often proprietary. Deportment can also be highly variable, as In may concentrate in other minerals such as chalcopyrite (e.g. in Southwest England, Andersen et al., 2016), meaning it would likely avoid the typical Zn processing route. The few studies on deportment which can be found (see Werner et al., 2015 and Table S1 in the Supporting information), suggest that some 5–35% of milled In typically appears in Zn concentrates. Taking Australia as an example, we can look at the historical production of Zn in Australia's mining sector, apply assumptions on average In grade as per Werner et al. (2017) and see that Australia may have exported some 18.5 kt In in Zn concentrates since 1889. Around half of this is likely to have been sent to processing facilities that have no In capability, meaning it most likely ended up in slags, and the other half possibly making it to production (albeit with downstream processing losses, see Werner et al., 2016).

The likelihood of currently unprocessed concentrates from the operating deposits in our database entering the In supply chain is dependent on numerous economic factors, including the processing capabilities of existing pipelines and the grade of In in these concentrates. We have attempted to characterise these factors in Figs. 9–11, which we believe to be a useful reference for future studies into In provenance. These maps highlight numerous locations outside of currently producing countries containing deposits with elevated calculated In grades as well as existing Zn processing capacity. Hotspots for Zn processing capacity are broadly in keeping with the distribution of global refined Zn production (see OCE, 2014), and locations coloured deeper red in Fig. 11 represent areas with an increased likelihood of In production from concentrates being economic in the event of In price increases. This map was produced using the grades obtained from the "Weighted Mean" estimate presented in Part II of this study (Werner et al., 2017). Green (2012) indicates that concentrates containing at least 300 ppm In are necessary for In to be economically extractable under current market conditions, although it has previously been noted that some concentrates are still processed to recover In at grades of around 100 ppm In (Phipps et al., 2008). This suggests that, assuming an average enrichment factor of 7 between deposit and concentrate grades (see Supplementary Table S1), many of the concentrates derived from deposits in our database are already economically viable, as shown in Fig. 11, which highlights that concentrates already derived from countries like Australia, the United Kingdom and South Africa may be targets for further exploitation.

The current dominant barrier to by-product extraction within Pb-Zn pipelines is that these by-product metals are often outside the source mining company's core business (Willis et al., 2012). This means that the quantification of the adaptability embedded in the In supply chain at a company level (also referred to as 'capacity readiness', Leal-Ayala et al., 2014) requires the identification and cataloguing of In capable facilities that are controlled by companies who also own non In producing facilities. One example of this is the Auby processing facility in France which is operated by *Nyrstar*, who in turn operate processing facilities in Australia which are not currently capable of separating In. Given their plans to establish In refining capacity in Australia (Nyrstar, 2014), it would appear they have confidence in continued growth in the In market. A full analysis of In processing capabilities at the company level globally is outside the scope of this report, however this is expected be the subject of future work by the authors of this paper. Indium refining capacity appears to have been studied at some level by the International Lead-Zinc Study Group, although their reports are not publicly available.

6.3. Mine wastes as a potential augment to indium supply

Previous research has highlighted how the processing of In has led to significant wastage throughout the 20th century. Despite improvements in downstream manufacturing, this largely continues today at the extraction phase, meaning that enormous quantities of In may have accumulated in mine wastes across the globe (Werner et al., 2015). The order of magnitude of mine wastes can be simply inferred by examining historical grade and production data and by combining these data with knowledge of the apportionment of In during the early stages of ore processing. Here, we use Broken Hill, Australia, as a case study for a large mine containing In in a country that does not currently produce In. Annual grade and production data for 1883–2011 indicate that over 10 kt In was milled during this period (data updated from Mudd, 2010). Some 5%–35% may have accumulated in tailings (Fig. 12, see also Supplementary Table S1 for specific references citing In deportment), and our database suggests that the main orebody at Broken Hill currently contains 1675 t In, which is analogous to the quantities calculated for the tailings currently residing at Broken Hill. Extrapolating this calculation to the rest of our deposit database indicates that global tailings resources may rival the contained In within unexploited but known mineral deposits. However, the marginal costs of extraction from these mining wastes are likely to prohibit the economic viability of some of these resources, although the sheer quantities of In (and almost certainly a wide variety of other metals) that are present in these tailings and wastes means that they are certainly worth further investigation. Further data and figures on Broken Hill are provided in the Supporting information.

6.4. Market considerations and estimation of indium-related value within mineral deposits

Indium has to date been exclusively extracted as a by-product, a fact that is reflected in the proportional contribution of In to the resource value of individual deposits (Mudd et al., 2016, 2017). Here, we demonstrate this by plotting normal distributions of the contributions to a deposit's monetary value using 2013 prices (from OCE, 2014; Tolcin, 2014) for deposits with known In contents that are reported with other base metal grades (Fig. 13). It can be seen in Fig. 13 that the median proportional resource value for In is ~10%. The fact that these curves have been developed from reported deposits that theoretically represent deposits with the greatest potential for profitability from In extraction means that these curves may well represent the upper bounds of proportional In resource value. This is supported by Fig. 13, as the In in these deposits can be seen to contribute a similar proportional resource value to Pb. However, given that many of the deposits in the reported database are not likely to be a part of the In supply chain, this also highlights that the quantity and price of a commodity alone are not enough to reflect the potential profitability of its extraction, when all costs are considered.

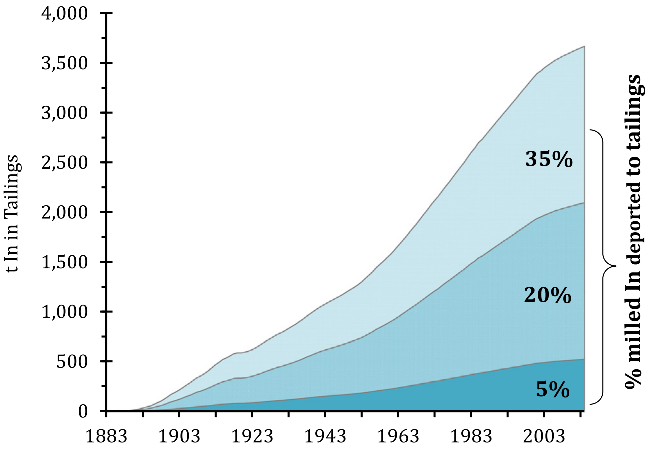

Fig. 12. Potential In accumulated in tailings at Broken Hill, Australia, 1883–2014. Assumes a range of 5–35% of milled In deporting to tailings.

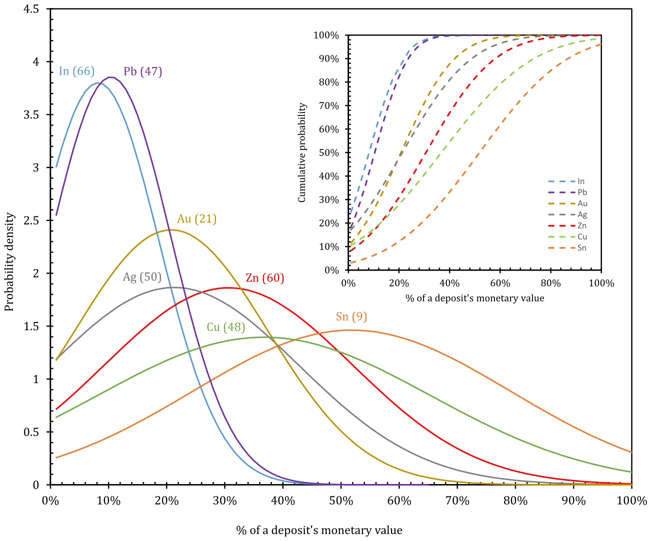

Fig. 13. Distribution of monetary value from 66 deposits reporting indium content and other base metal grades. Numbers in brackets indicate the number of deposits reporting the commodity from which the normal distribution is derived. Insert: Cumulative probability plot, indicating that a metal contributes less than x % of a deposit's resource value, with y % probability).

A similar distribution of monetary value was produced for the deposits with inferred In content in the Pb-Zn database (see Supporting information). The median resource value of In in these deposits was calculated at ~6%, which verifies the proxy estimates employed in Pt. II (Werner et al., 2016), as it would be expected that the median In value in these deposits is below 10%, given that they have not been reported. Metals commonly have more volatile prices than other commodities, with In being amongst the most volatile (de Groot et al., 2012). However, the demand for In is quite inelastic to fluctuations in the In price, primarily as the costs of In are likely to be very small in comparison to that of other metals present in its primary end uses (O'Neill, 2010). The increased recovery of previously wasted In during fabrication and manufacturing stages led to price drops and stabilised primary production in the last decade, although this has not dampened projections for this decade (e.g. a 14.1% price increase for 2010–20, de Groot et al., 2012). Green (2009) assessed grades and tonnages from a select number of In-bearing deposits and concluded that resources are sufficient to sustain upwards of 1 kt In/year primary production, although there are a limited number of deposits which could provide In as a primary commodity, and then only for a few years. While we have not directly assessed the economics of extracting In from each of the deposits in our database, we have identified deposits with sufficient quantities to supply national or even global markets for many years, suggesting that resource quantities are not likely to be a limiting factor in In becoming a primary commodity. Changes in demand will still be speculative and are dependent on factors such as dematerialisation strategies, changes in technologies such as PV modules (Woodhouse et al., 2012), and by extension the substitutability of In (see Graedel et al., 2015). Further research into the nature and adaptability of the global In market is necessary to understand specific pricing thresholds and the ability of the global resources identified in this study to translate to supply. Ideally, this research would also further explore the potential oversupply of Zn necessary to meet future In demand (as per Elshkaki and Graedel, 2015).

6.5. Uncertainties and other avenues for further research

Although our database is reasonably comprehensive in representing In-bearing deposits, there are undoubtedly some uncertainties relating to the compilation of the reported deposit database and the specific data sources employed for this study. The uncertainties involved in the general methodology employed here are discussed extensively in Part II of this study, including uncertainties associated with the use of proxies for inferring In grades (Werner et al., 2017). Here, we focus on uncertainties and avenues for future work which relate specifically to the data and sources employed for our assessment of In.

Our development of the reported resource database (Table 1 and Supporting information) highlighted that many deposits containing reported In concentrations were no longer operating. This created challenges in terms of understanding the quantities involved in economic terms and determining which values should actually be included within our database. For example, the Toyoha deposit in Japan produced In for many years and the closure of this site strongly suggests that the In at this location is no longer economic; however, the tonnage and grade estimates utilised in this paper were published on the year of its closure (see Ishihara et al., 2006), suggesting that there were still quantities of In remaining at that time. As such, we have included this deposit in our database on the grounds that known quantities in known deposits should be included in a global metal resource assessment, although this undoubtedly introduces some uncertainty. In addition, more detail on the remaining resources associated with individual deposits could be achieved using yearly processing data for the deposits listed in our database to determine how much In had been extracted at a given point in time. This would then generate specific values that would reflect any changes that occurred since the publication of a resource estimate. This process was previously undertaken for the Heath Steele and Brunswick 6–12 deposits in Canada, primarily as these deposits have abundant data relating to In production (Werner et al., 2015), and for Broken Hill during this study, although it is clearly beyond the scope of this paper to undertake the same analysis for the remaining 98 deposits, most of which are, in any case, unlikely to have the necessary data to perform yearly production analyses. It should also be noted that any risk of overestimation from these analyses is undoubtedly counteracted by the fact we have not included Sn deposits within our analysis and the fact that our In estimates provide minimum rather than maximum values, as described above. Including Sn deposits within global In resource estimates would require the compilation of a global database of sn-bearing deposits and the analyses of these deposits to identify and characterise the elevated In grades observed in some Sn mineralisation (Pavlova et al., 2015), a task that is well beyond the scope of this paper.

Another source of uncertainty arises from the seemingly high sensitivity of our results to the work of the relatively few authors who work in this field, such as Shunso Ishihara and Ulrich Schwarz-Schampera, both of whom have contributed extensively to our knowledge of In deposits and resources. Studies such as Murakami and Ishihara (2013), Schwarz-Schampera and Herzig (2002), and Schwarz-Schampera (2014) have provided useful summaries of the state of prior geological research and enabled many ‘medium’ and ‘low’ deposits in our reported database to be identified and quantified, which otherwise might not have contributed to our global resource estimates. The input of these sources is another reflection of the state of In reporting, as other studies employing per-deposit analyses of global resources, even for other by-product metals such as cobalt, rely less on academic literature, and more on industry reporting (see Mudd et al., 2013b).

End-of-life wastes, such as consumer electronics which contain In and have become e-waste, have also not been addressed in this study despite much discussion of their potential to augment In supply. For example, Duan et al. (2015) highlight urban mining as a promising solution to meeting China’s demand for In, highlighting that China has become a net importer of refined In in recent years despite their status as the dominant exporter of In and their considerable resources, as identified in this study. Improvements in In recovery from end of life wastes are to be expected over time, but approximately 80% of In end uses remain unrecyclable or are dissipated (Ciacci et al., 2015). This suggests that recycling alone will not be enough to meet growing demand, a sentiment echoed by Bloodworth (2014). In addition, Yamasue et al. (2009) found In to be the only case in which the total material inputs required to produce primary In were actually lower than that of In sourced from end-of-life recycling. This suggests that primary In deposits may play a more vital role in the future supply of this metal than other critical metals of interest for their recycling potential. The seemingly conflicting conclusions on the future sourcing of In highlight the conversion of virgin materials or wastes to supply as an avenue for continued research.

7. Conclusions

This study presents a compilation and analysis of 1512 mineral deposits that host In-associated mineralisation, using the best available information to estimate the quantities of In in each of these deposits. This indicates that at least 356 kt (or 380 kt, including regional estimates) of In is present in known mineral deposits and a further minimum of 24 kt In in mining waste projects, which is sufficient to meet demand for In well into the next century, even without consideration of the potential for supply from secondary sources. While China is by far the dominant producer of refined In at present, significant quantities of In exist outside of the current suite of producing countries. This suggests that in the event of a supply restriction, In capacity could be developed elsewhere, although there are numerous challenges in converting dormant resources into supply. Australia and Bolivia notably contain large In resources and have not historically produced refined In, although they may already supply In-laden Zn concentrates to other countries for refined In production. The monetary value of reported and inferred In contents across our databases were also analysed, suggesting that In may contribute ~6% and ~10% of a deposit’s resource value in deposits where it is unreported and reported, respectively.

Global In resources are dominantly hosted by sediment-hosted Pb-Zn deposits, which contain the equivalent of VMS, skarn, epithermal and porphyry deposits combined in our deposit databases, indicating a clear relationship between the base metals concentrated in these deposit types (e.g. Zn and to a lesser extent Cu) and In abundances. However, the majority of these quantities are inferred, not reported, highlighting the need for better reporting of by-products/critical metals. Overall, the In grades of many deposits appear sufficient to justify continued improvements in In processing efficiency. Our study also indicates that robustly compiled and assessed resource estimates such as the one presented here should be the preferred basis of policy development and mineral exploration programs. It is hoped that our results may rest questions of ‘how much is left’, and prompt a shift towards greater focus on the impacts of extraction from different sources. With detailed knowledge of the size and spread of In resources in known deposits, steps can be made towards strategic and sustainable sourcing of In as required for this century's transition to renewable energy, increased use of digital display technologies, and/or other future applications of In.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.oregeorev.2017.01.015.

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