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Quantifying the recoverable resources of by-product metals: The case of cobalt

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ABSTRACT

The long-term availability of mineral resources is crucial in underpinning human society, technology and economic activity, and managing anthropogenic environmental impacts. This availability is increasingly true for metals that do not generally form the primary product of mines, such as copper or iron, but instead are recovered as by-products (or sometimes co-products) during the processing of primary ores—also known as 'companion metals' (e.g., indium, cobalt, molybdenum, rhenium, selenium). These metals, however, can be of significant economic and technological importance, both to a mine's economics and in downstream applications. It is therefore useful to develop methodologies to estimate the "recoverable resource" for such companion metals, i.e., the amount that could, if desired, be extracted and put into use over the next several decades. Monitoring the supply and demand of these resources is important to enable the identification of any changes that may have significant repercussions for the global economy, technology needs, and the environment. Here, we derive an estimate of the recoverable resource for cobalt (Co), a metal used with increasing frequency and in larger amounts in modern technology that is mainly recovered as a by-product of copper and nickel ore processing and production; Co-only mines are few in number and typically small in size. Our methodology combines the reported size of ore bodies that host Co with measured or estimated Co concentrations in the ores within these bodies. The dominantly by-product nature of Co means that uncertainties exist for some of the Co grades as well as recovery rates; given this, we also split our total recoverable Co resource, using a resource estimate data quality classification, into high, medium and low quality data, depending on factors such as whether statutory resource reporting codes were used during resource reporting. This methodology indicates that a minimum of 26.8 Mt Co is present in current global Co resources, with 15.2, 5.6 and 6.0 Mt Co in high, medium and low quality resources, respectively. Applying typical recovery rates for different ore types indicates that ~15.9 Mt of this Co is recoverable, with ~10.7, ~2.6 and ~2.6 Mt Co recoverable in high, medium and low quality resources, respectively. This approach provides a basis for determining similar recoverable resource estimates of other companion metals, such as indium, rhenium, selenium, etc., all of which are of increasing importance in modern day life.

1. Introduction

Although economic geologists and exploration and mining companies know well that the majority of metals are not mined for themselves (unlike host metals such as iron or aluminium) but are recovered as by-products or co-products from parent ores, the majority of people outside of this community do not. By-products are often referred to as 'companion metals' in industrial ecology, and this relationship between companion and host metals indicates that the availability of by-product-derived metals is dependent on the availability of technology to recover those metals during or following processing of the host metal ore, as well as on the economic attractiveness of companion or by-product metal recovery. The effects of such variables result in one or both of these constraints limiting the production of desirable companion metals. Hence, it is important to define a number of key parameters in order to make a realistic estimate of anticipated companion metal availability, namely: (1) the size and type of the host metal ore bodies; (2) the characteristic abundances of companion metals in the host or hosts; (3) the typical recovery efficiencies for these companion metals (especially the different technologies used); and (4) models of the relative costs and benefits of companion metal recovery.

Rapid increases in the use of companion metals in the past few decades, together with supply shortages occurring from time to time, have raised concerns about the long-term stability of the supplies of some of these metals. For example, in the late 1990s, world cobalt demand grew rapidly due to increased use in the aerospace industry and batteries, but this increased demand coincided with major supply uncertainty from Africa, leading to substantial market volatility (Seddon, 2001).

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Evaluating the long-term prospects for different metals is an exercise in geology, technology, and economics—all factors that can be quite variable over time (as well as recognising that social and environmental factors can also be important, e.g., bans on mining in national parks, policies to address 'conflict' minerals, labour costs, etc.). For many companion metals there are no reliable estimates of ore reserves or mineral resources (Crowson, 2011). For example, although the U.S. Geological Survey (USGS) publishes annual estimates of global reserves for primary metals such as iron (Fe), copper (Cu), gold (Au) and others, no estimates exist for companion metals such as indium, gallium, germanium and scandium (USGS, 2012). It is therefore useful to prepare estimates, even if approximate, of what might be termed the "recoverable resource" for a particular companion metal. This parameter provides perspective, at least in a relative geological sense, on potential supply limitations over the coming century.

Here, we address the first of the uncertainties related to companion metal availability, that of quantifying the recoverable resource. We do so for cobalt (Co), a metal used with increasing frequency and in larger amounts in modern technology, and one recovered almost entirely as a by/co-product of the mining of copper (Cu) and nickel (Ni) ores. Reserve-resource data are also more readily available for Co than other companion metals, thus the methodology developed herein provides a robust model for constructing similar estimates for other companion metals.

2. Background on cobalt

Cobalt has been used for centuries in the production of pigments, but it was only in the 19th and 20th centuries that the metal began to be included in various alloys and as a catalyst in industrial chemical processes (Hawkins, 2001). The result, especially since the mid-20th century, has been rapidly increasing rates of use. Historical global mine production and nominal and real prices are shown in Fig. 1. The rapid decline in production around 1980 was due to the so-called 'Shaba incident', whereby civil unrest in Zaire (now the Democratic Republic of Congo or DRC, then the predominant global producer of Co) led to significant fears of world supply shortages, which was followed by rapid price increases over a few months and subsequently by substitution that dampened Co demand for a decade. Beginning in the early 1990s, world Co production and demand have undergone strong growth, reaching new records by the late 2000's before the global financial crisis temporarily lowered demand.

Contemporary uses of Co are diverse. Harper et al. (2012) determined that in 2005 about 22% of Co production was used in superalloy manufacture, the majority within gas turbines and jet engines, with 22% used in batteries, 11% in catalysts, 11% in "hard metals" (dies, metal cutting tools, and mining bits), and 27% in tire adhesives, pigments, other alloys, and a few other minor applications.

In general, most Co occurs with Cu and Ni ores, making Co a classic companion metal. Co extraction is, as eloquently noted by Smith (2001, p. 75), "always the bridesmaid and never the bride"—meaning it is nearly always a secondary product to Ni or Cu, and is rarely ever the primary metal of economic interest for a mining project. Although historically Co-dominant mining fields have been important, such as Cobalt in Ontario, Canada or Blackbird in Idaho, USA, such districts are relatively rare and generally small in scale compared to Ni–Cu projects—at present, the only known Co-dominant mines operating are in Bou Azzer, Morocco. The recovery efficiency of Co from the host ores is variable and generally low (De Cuyper, 1988), and much of the Co deports to mine tailings or smelter slags (Shedd, 1993; Vítkova et al., 2010).

Some two-thirds of all cobalt entering use is fabricated into final products in only three countries: China, Japan, and the United States (Harper et al., 2012). These countries, however, are not major sources of Co—Japan has no Co resources, and those of China and the United States are small in proportion to those of several other countries. Supply constraints therefore could be a concern for product-manufacturing countries, especially because of the increasing use of Co in batteries (in 2006, Co use in batteries exceeded that in superalloys; see USGS, 1994–2010, 2006 edition—Cobalt).

For many years, the USGS published estimates of the global "reserve base" of a number of metals. It ceased to do so in 2009, however, and there is no ongoing effort to fill this information gap despite the need for such analyses as input to considerations of long-term resource sustainability. The approach we follow herein addresses this need for companion metals and makes such estimates more transparent and justifiable.

3. Cobalt Geology, Mineral Resources and Extraction

3.1. Basic Geology and Mineral Deposit Types

Cobalt is a widely dispersed yet uncommon element, averaging about 17.3 mg/kg in continental crust (Rudnick and Gao, 2003). It is, however, typically found in higher concentrations in mafic–ultramafic igneous rocks in close association with Ni (Donaldson and Beyersmann, 2010). Although the most important Co minerals are sulfides, including linnaeite (Co_3S_4), siegenite ($(Co,Ni)_3S_4$), carrollite (Co_2CuS_4), and cobaltite (CoFeAsS), the majority of production is based on Co substitution into other sulfide minerals (e.g. arsenopyrite, pyrrhotite, pyrite, or pentlandite; Donaldson and Beyersmann, 2010).

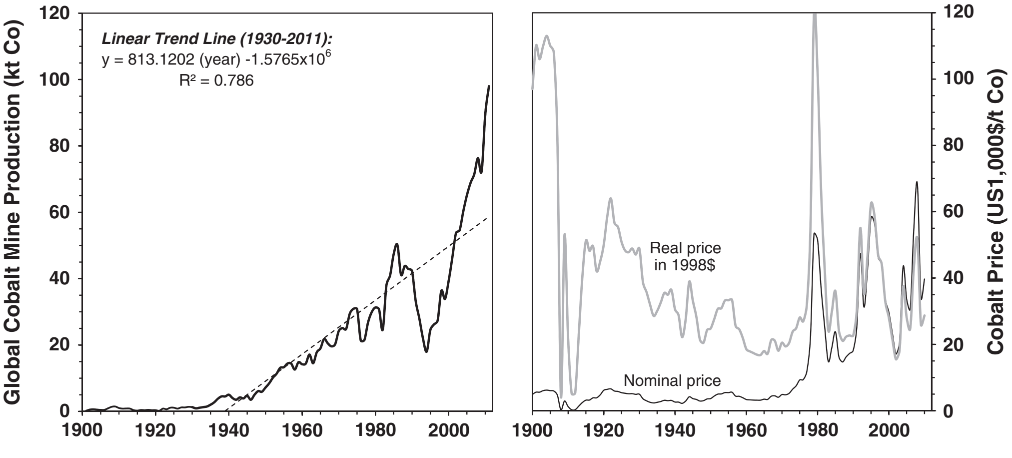

Fig. 1. Historical global cobalt mine production, including linear trend line from 1930 to 2011 (left; data compiled from CDI and WBMS, 2008; USGS, 1994–2010); Co price in nominal and 1998$ (right; data from Kelly et al., 2012).

Cobalt mineralization typically comprises Cu–Co sulfide, Ni–Cu–Co sulfide or Ni–Co laterite ores, although Co is almost invariably extracted as a by-product to the principal metal, be it Cu, Ni, or in some cases other metals such as the platinum group elements (PGEs). There are seven major Co-containing mineral deposit types (adapted from Dalvi et al., 2004; Elias, 2002; Galley et al., 2007; Goodfellow and Lydon, 2007; Jowitt and Keays, 2011; Jowitt et al., 2012; Meinert et al., 2005; Mudd et al., in press; Naldrett, 2004; and references therein):

1. *Magmatic sulfide deposits*—mafic and ultramafic intrusive igneous rocks, forming massive or disseminated Fe–Ni–Cu sulfide ores that contain significant Co up to several hundred parts per million (~500 to 1000 mg/kg). The Sudbury Basin of northern Ontario, Canada, and the Nor'ilsk–Talnakh field in Siberia, Russia, are premier examples.
2. *Skarn, contact metamorphic or magmatic-hydrothermal deposits*—felsic to mafic magmatic intrusion-related rocks hosting magnetite, chalcopyrite, and Co-containing pyrite ores that formed during porphyry-type mineralization and/or contact metamorphism of sedimentary, typically carbonate, rocks, including Iron Oxide–Copper–Gold (IOCG) deposits. The Cornwall and Morgantown deposits in Pennsylvania, USA, are the best known examples.
3. *Laterite deposits*—surface weathering of ultramafic (olivine-rich) rocks such as peridotite and serpentine can form lateritic soil profiles rich in Fe, Ni and Co. Major lateritic deposits occur at or near the equator, especially in Cameroon, Cuba, New Caledonia, Indonesia and the Philippines, as well as in temperate and arid regions such as Australia, the United States, Madagascar, and Russia. The weathering leads to distinct ore sub-types, namely limonite, nontronite, and saprolite/garnierite/serpentine, with different impurity levels of magnesium, Fe, and silica, as well as transitional ore types.
4. *Volcanogenic massive sulfide deposits*—formed by submarine-hydrothermal processes in ancient volcanic rocks, these ores consist mainly of pyrite or pyrrhotite. In the context of Co, the most important examples are deposits in the Outokumpu district of Finland and the Windy Craggy deposit in British Columbia, Canada.
5. *Vein or replacement deposits* that are mined specifically for Co. The Cobalt-Gowganda region of northern Ontario in Canada had grades reaching 10% Co in some veins, whereas the Bou-Azzer area of Morocco contains an average of 1.2% Co in veins. The Co grades in replacement deposits are generally about 0.2 to 0.5% Co, as exemplified by deposits in Burma.
6. *Stratiform sediment-hosted deposits*—Co mineralization in folded shale and dolomite containing mainly Cu–Co sulfides. The predominant region is the Katangan Cu-belt in central Africa; other examples include the giant Talvivaara black shale-hosted Ni–Zn–Co–Cu–U resource in Finland, and the modest Co resource at Pyrite-Big Hills near Broken Hill, Australia.
7. *Chemical precipitate deposits*—these deposits are associated with iron (Fe) and manganese (Mn) precipitation, either in the peripheries of seafloor hydrothermal systems, and during the formation of Fe–Mn nodules and crusts on the ocean floor and seamounts, or during weathering as at Mt Tabor in Australia.

There are also other mineral deposit types which are known to contain Co but are not included above, since Co is not extracted from such mines at present and this is unlikely to change in the future. This is exemplified a number of unconformity-related uranium (U) deposits in Saskatchewan, Canada, that have substantial grades of Ni, Co, Cu and As, but the radioactivity of the ore means that it is impractical and uneconomic to extract such metals, and hence only U is recovered.

3.2. Processing of stratiform sediment-hosted Cu–Co ores

Stratiform sediment-hosted Cu–Co ore resources are economically dominated by the Katangan Cu-belt of central Africa, a region that stretches over 500 km from Zambia into the DRC. Here, the Lufilian Arc hosts a number of deposits that are exploited by numerous active mines; these mines have supplied ~25–50% of world Co production since the 1970s (Smith, 2001). Nearly all projects in the DRC have minority or controlling interests by the DRC Government through state company La Générale des Carrières et des Mines, better known as Gécamines, formed in 1966 from the nationalisation of Belgian company Union Minière du Haut Katanga. In contrast, most projects in Zambia are run by mining companies that are listed on their respective national stock exchange (e.g., Metorex in South Africa, First Quantum in Canada). Average ore grades can range from 0.2 to 1% Co, accompanied by 1–3% Cu, with deposit sizes ranging from 5 to >500 Mt of ore.

Mining uses conventional open cut or underground techniques, followed by crushing, grinding, and flotation to produce concentrates for smelting and refining. Most sulfide ores are processed using traditional froth flotation, with flotation using palm oils utilized at some oxide ore projects (Bulatovic, 2007, 2010; Crundwell et al., 2011); some projects directly leach the ore using acids. Concentrates are treated either by leaching and solvent extraction-electrowinning, or through pyrometallurgical techniques. The recent recovery rates for some African Cu–Co projects over time are shown in Fig. 2. In addition, the shale-hosted Talvivaara Ni–Cu–Co–Zn–U project in Finland has successfully implemented bioheap leaching, with production starting in 2008.

3.3. Processing of magmatic Ni–Cu–Co sulfide ores

The various magmatic Ni–Cu–Co sulfide fields around the world yield diverse quantities of Co; important producers include the Sudbury field, Voisey's Bay, Thompson, and Raglan projects in Canada; the Bushveld Complex in South Africa; the Nor'ilsk–Talnakh field in Russia; Jinchuan in China; and Kambalda in Australia. Each field has distinct geological characteristics with widely varying Ni–Cu–Co–PGE grades (Crundwell et al., 2011; Glaister and Mudd, 2010; Mudd, 2010b; Warner et al., 2007). Average Co ore grades are typically low, ranging from 0.01 to 0.1% Co, with 0.5–3% Ni, 0.2–3% Cu and highly variable PGE grades of 0.1–10 g/t; deposit sizes range from 1 to >1000 Mt of ore (see Mudd, 2010b, 2012; Mudd et al., in press).

The mining techniques used are either open cut or underground, with some fields using both methods concurrently. All ores are crushed and ground, with flotation used to produce sulfide concentrates for

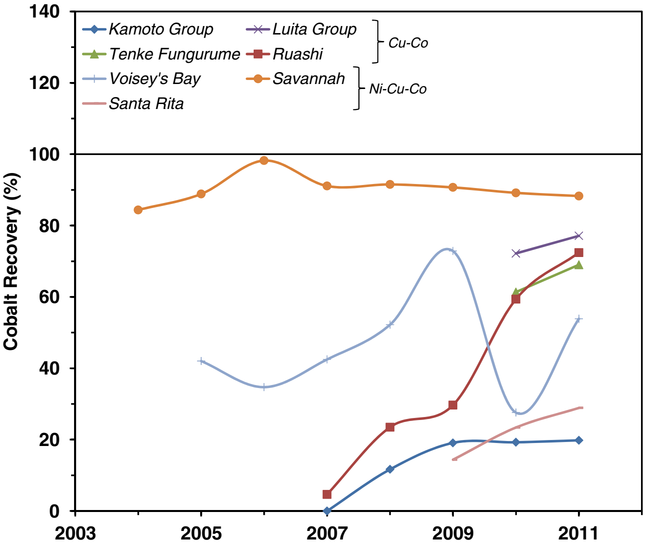

Fig. 2. Recent Co recovery rates at selected Cu–Co stratiform sediment-hosted and Ni–Cu–Co magmatic sulfide projects (data calculated from respective company annual and/or quarterly reporting).

smelting and the matte processed in a refinery. The Co is generally extracted at the refinery, either as a Co chemical (e.g., Co chloride or sulfate), or as a Co cathode by solvent extraction and electrowinning. Recent recovery rates for three Ni–Cu–Co sulfide projects are included in Fig. 2.

3.4. Processing of Ni–Co laterite ores

The average ore grades for Ni–Co laterite ores can range from 0.1 to 1% Co and 0.5–2% Ni, with deposit sizes ranging from 5 to >500 Mt of ore. Given the surficial nature of laterites, they are invariably mined by open cut methods. The processing of laterite ores is relatively complex, due to the difficulty in separating the Ni and Co from the host silicate matrices. Three primary process systems are used currently: rotary kiln electric furnaces (RKEF), the Caron ammonia leach process, and high pressure acid leaching (HPAL). In general, laterite ore sub-types are suited to a particular process, such as limonite for HPAL or saprolite for RKEF (King, 2005; Warner et al., 2006). This trend is changing, however, as new laterite projects are being engineered to treat all ore types, typically using either HPAL or potentially heap leaching. At present, there are only four Caron plants still operating (plus one closed plant), three HPAL projects in operation (plus two closed and several new projects under development), and a large number of RKEF plants (>20). New processes currently being investigated include heap leaching (e.g. Murrin Murrin, Australia, Readett and Fox, 2010; also the bioheap leach process at Talvivaara, Riekkola-Vanhanen, 2010), an atmospheric leach process being developed by Anglo American (the ‘ARNi’ process; Steyl et al., 2008) and the new DNi hydrometallurgical leaching process by Direct Nickel. Given the lack of reported Co grade data for operating Ni laterite projects, it is not possible to show recovery over time.

3.5. Processing and extraction—summary

A summary of Co production by project for 2011 is given in Table 1 (based on available data), with Co production by country listed in Table 2. Many projects do not report Co grades in annual production data, such as those owned by Norilsk Nickel, a company that accounts for ~8% of world Co production (Norilsk, 2012), as well as several other projects that do not publicly report any production data (especially private companies or Chinese and Russian projects, as well as some Cuban projects). Most laterite projects using RKEF plants do not focus on Co production, and nearly all projects report only Ni-related data despite their extraction of Co in the final refining stages. For example, the Doniambo RKEF plant in New Caledonia produces ferronickel and Ni matte, which is sold to Eramet's Sandouville refinery in France to produce refined Ni as well as Co chloride; however, no Co production data are published by Eramet. In contrast, PT Inco reports Co production data for the Sorowako RKEF plant in Indonesia, although neither the grades in mineral resources nor the amount of ore processed.

Table 1 shows that Co extraction overall is highly variable, with our calculated recoveries ranging from 10 to 95% (i.e., low recoveries indicate significant Co loss to mine tailings or smelter slags). Furthermore, there is no apparent link to ore grade, as some sulfide projects have low recoveries while others with similar grades have high recoveries; hence, Co recovery is intrinsically linked with deposit mineralogy (e.g., oxide versus sulfide ores) and the processing technology used (e.g., flotation or hydrometallurgy). Furthermore, some projects focus pre-dominantly on Ni or Cu recovery (or both) to the detriment of Co recovery (often linked to market prices and the relative costs of recovery). In general, Cu–Co projects can achieve large annual Co production (~3000 to 10,000 t Co/year), Ni laterite projects have more moderate Co production levels (~1000 to 4000 t Co/year), and Ni–Cu sulfide projects have generally small annual production levels (~50 to 500 t Co/year). PGE projects produce very small quantities of Co, generally <50 t Co/year, with Co contributing <0.1% of annual revenue.

4. Hybrid methodology for quantifying recoverable cobalt

4.1. Mineral resource reporting

A variety of common terms are used to describe or quantify economic mineral resources, including some having statutory significance in many countries. A mineral resource can, at its simplest, be considered as material that can generate inherent value to society, with examples being steel for structures, copper for electrical wiring and pipes, gold for jewellery or electronics, or lithium for energy storage. A mineral resource is identified through geological exploration and, if considered profitable, can be mined to produce a given mineral or metal. The challenge is to ascertain and describe which deposits constitute a potentially profitable mineral resource. This determination can vary due to market conditions (e.g., supply/demand and price fluctuations), input costs (e.g., diesel, electricity, labour), ore processability (e.g., how easily the minerals can be extracted with different technologies and the relative costs and benefits involved in targeting mineral processing for individual metals, such as Ni over Co), capital and operating costs, or social issues (e.g., bans on mining in national parks, environmental restrictions, political and trade sanctions).

Given the complexity of demonstrating the profitability of mining a mineral deposit and the need to provide clear justification and communication of such results to the public and investors (as most mining companies are publicly listed on their respective national stock exchange), the global mining industry uses formal codes for assessing and reporting mineral resources. In general, all mining companies listed on a stock exchange are required to use their national code. In Australia, companies use the Joint Ore Reserves Committee (or ‘JORC’) Code (AusIMM et al., 2004; Stephenson, 2001), while Canada has National Instrument 43-101 (or ‘NI 43-101’; OSC, 2011), and South Africa has the South African Mineral Resource Committee Code (‘SAMREC’; SAMRCWG, 2009), amongst others (e.g., Russia, China, Europe, USA). A global committee was established in 1994 called the ‘Committee for Mineral Reserves International Reporting Standards’ (and known as CRIRSCO), auspiced through the Council of Mining and Metallurgical Institutes, to provide for international co-operation on reserve-resource reporting codes. The member regions or countries of CRIRSCO include Australasia, Canada, Chile, Europe, South Africa and the USA.

The two primary aspects that all statutory codes consider in claiming a mineral resource as profitable are geological and economic probability. A range of important ‘modifying factors’ are compulsory to consider, such as mining, metallurgical, economic, marketing, legal, environmental, social and governmental. The primary categories used to classify a mineral deposit are ore reserves and mineral resources. The typical distinction is that ore reserves have a very high economic and geologic probability of profitable extraction, whereas mineral resources have a reasonable geological probability but are less certain economically. Commonly used definitions (e.g., JORC) are:

- *Ore reserves*—assessments demonstrate at the time of reporting that profitable extraction could reasonably be justified. Ore reserves are sub-divided in order of increasing confidence into probable ore reserves and proved ore reserves.
- *Mineral resources*—the location, quantity, grade, geological characteristics, and continuity of a mineral resource are known such that there are reasonable prospects for eventual economic extraction, although not all modifying factors have been assessed and hence some uncertainty remains. Mineral resources are sub-divided, in order of increasing confidence, into Inferred, Indicated, and Measured categories.

In general, most statutory codes allow the reporting of mineral resources as inclusive of, or separate to, ore reserves, while some

Table 1

Available mineral processing data for Co-producing mines (2011 production data only).

Mine/project	Ore type	Primary process	Mt ore	%Ni	%Cu	%Co	kt Ni	kt Cu	t Co	Co recovery	Companies
Murrin Murrin, Australia	Ni laterite	HPAL + heap leach	2.7	1.3	–	**~0.10**	30.0	–	2100	**~75%**	Glencore (through Minara Res.)
Moa Bay, Cuba	Ni laterite	HPAL	**~3.0**	1.26[a]	–	0.13[a]	34.6	–	3854	**~90%**	Sherritt Int., Cuban Gov't
Coral Bay, Philippines	Ni laterite	HPAL	*nd*	2.3[a]	–	*nd*	**~20**	–	**~1500**	*nd*	Sumitomo, Mitsui, Sojitz, Rio Tuba
Sorowako, Indonesia^{2010}	Ni laterite	RKEF	4.176^{2010}	2.00^{2010}	–	*nd*	78.4^{2010}	–	1,196^{2010}	*nd*	Vale Inco, Sumitomo (via PT Inco)
Goro, New Caledonia	Ni laterite	HPAL	1.043	1.29	–	0.11[a]	5.1	–	245[b]	**~21%**[b]	Vale Inco, SNN, SPMSC
Niquelândia[c]	Ni laterite	RKEF	3.423	**~1.15**[c]	–	0.099	31.0	–	1835.7	54.1%	Votorantim Group[c]
Fortaleza-Prometálica[c]	Mag. sulfide	Flotation-Smelter	0.893	**~1.75**[c]	nd	0.026	11.7	nd	219.1	94.6%	Votorantim Group-Prometálica[c]
Sudbury (Xstrata), Canada	Mag. sulfide	Flotation	1.884	1.46	3.23	0.07[a]	22.7	49.9	473	**~36%**	Xstrata
Sudbury (Vale Inco), Canada	Mag. sulfide	Flotation	5.612	1.45	1.61	0.04[a]	59.7	101	593	**~26%**	Vale Inco
Voisey's Bay, Canada	Mag. sulfide	Flotation	2.366	3.38	2.39	0.12[a]	68.9	51	1585	**~56%**	Vale Inco
Thompson, Canada	Mag. sulfide	Flotation	1.903	1.61	0.10[a]	*nd*	25.0	1	158	*nd*	Vale Inco
Raglan, Canada	Mag. sulfide	Flotation	1.206	2.39	0.69	0.07[a]	27.3	7.2	561	**~66%**	Xstrata
Redstone, Canada	Mag. sulfide	Flotation	0.017	0.45	**~0.05**[a]	0.03[a]	0.1	<0.1	2.1	**~40%**	Liberty Mines
Shakespeare, Canada[d]	Mag. sulfide	Flotation	0.152	0.314	0.368	0.019	~0.4[d]	~0.5[d]	~15[d]	**~50%**[d]	Ursa Major Minerals
Jinchuan, China[e]	Mag. sulfide	Flotation	~8.3[e]	~1.3[e]	~2.4[e]	~0.01[e]	~90[e]	~150[e]	~450[e]	**~55%**[e]	Jinchuan Group
Cosmos-Sinclair, Australia	Mag. sulfide	Flotation	0.769	2.69	*nd*	*nd*	17.0	0.9	396	*nd*	Xstrata
Savannah, Australia	Mag. sulfide	Flotation	0.637	1.52	0.74	0.08	8.3	4.5	439	88.3%	Panoramic Resources
Kambalda Group, Australia[e]	Mag. sulfide	Flotation	~1.04[f]	~2.88[f]	~0.23[f]	~0.06[a,f]	25.0[f]	1.9[f]	~137[f]	**~22%**[f]	Various[d]
Nkomati, South Africa	Mag. sulfide	Flotation	6.442	0.30	0.11	0.02[a]	12.0	5.8	~553	**~43%**	Norilsk Nickel, African Rainbow
Santa Rita, Brazil	Mag. sulfide	Flotation	5.373	0.50	0.14	0.02	15.9	4.9	273	28.9%	Mirabela Nickel
Munali, Zambia	Mag. sulfide	Flotation	0.652	0.74	~0.14[a]	~0.06[a]	3.0	~0.7	~100	**~25%**	Albidon, Jinchuan
Mimosa, Zimbabwe	Mag. sulfide	Flotation	2.320	0.14[a]	0.12[a]	*nd*	3.1	2.4	86	*nd*	Impala, Aquarius Platinum
Talvivaara, Finland[g]	Sed.-hosted	Heap Leach	11.1	0.22[a]	0.13[a]	0.02[a]	16.1	–	400[h]	**~18%**[h]	Talvivaara
Ruashi, DRC	Sed.-hosted	Flot'n-Leach-SX-EW	1.270	–	3.2	0.4	–	34.5	3678	72.4%	Metorex Group
Tenke Fungurume, DRC	Sed.-hosted	Leach-SX-EW	4.052	–	3.41	0.40	–	127.4	11,182	69.0%	Freeport, Lundin, Gécamines
Kamoto Group, DRC[i]	Sed.-hosted	Flot'n-Roast-Leach-SX-EW	4.096	–	4.38	0.49	–	~93.3[i]	~3,939[i]	19.8%	Katanga Mining, Gécamines
Mutanda, DRC	Sed.-hosted	DMS-Leach-SX-EW	*nd*	–	*nd*	*nd*	–	63.7	7900	*nd*	Samref Congo, Glencore, Rowny
Luita-Lubumbashi-Kakanda, DRC	Sed.-hosted	Flot'n-Roast-Leach-SX-EW	1.058	–	–	1.40	–	–	11,423	77.1%	Eurasian Natural Res., Gécamines
Etoile, DRC	Sed.-hosted	HMS-Leach-SX-EW	1.525	–	2.84	0.68	–	20.2	~1070	~10.3%	Shalina Resources
Mopani, Zambia	Sed.-hosted	Flot'n-Roast-Leach-SX-EW	*nd*	–	*nd*	*nd*	–	204.4	900	*nd*	Glencore, First Quantum, ZCCM
Konkola-Nchanga, Zambia	Sed.-hosted	Flot'n-Leach-SX-EW	9.065	–	~1.63	*nd*	–	200.0	**~1500**	*nd*	Vedanta Resources
									~58,763		

Notes: All data are from respective company annual and/or quarterly reporting; data in bold–italics are indirectly estimated based on other reported data (mainly historical data); *nd*—no data; SX–EW—solvent extraction and electrowinning; HMS/DMS—heavy/dense media separation.

[a] Mineral resource ore grade.

[b] Sales only, production would be slightly higher but is not reported; reported.

[c] Data for Niquelândia and Fortaleza-Prometálica from DNPM (2012), with grade estimated from contained Ni in ore.

[d] Shakespeare ore is sold to Xstrata's Strathcona mill in Sudbury; production is based on typical Sudbury field mill recoveries (Mudd, 2010b).

[e] Jinchuan does not regularly report annual production data, values are approximate only based on past data (see JGL, 2009).

[f] The Kambalda mill is owned by BHP Billiton while all mines are owned by junior companies who sell ore to Kambalda, and since the 2005 takeover of WMC by BHP Billiton, no production data for the Kambalda mill has been reported; the data shown are based on all junior companies and the authors' estimates (e.g. Mudd, 2010a).

[g] Talvivaara does not extract Cu (yet) but also produced 25,462 t zinc in 2010 (grade 0.49% Zn).

[h] Sales only, production would be slightly higher but is not reported, plus operations are still ramping up and recovery is still expected to increase gradually.

[i] Cu–Co production data are estimates from the mill only (approximated based on other reported data).

Table 2
Co mine production by country (2011).
Sources: NRC, 2012; USGS, 2013; WADMP, 2012.

Country	t Co	% Production
Dem. Rep. Congo	60,000	57.2
China	6800	6.5
Russia	6300	6.0
Zambia	5400	5.1
Australia	3851	3.7
Cuba	4000	3.8
Canada	2966	2.8
Morocco	2200	2.1
New Caledonia	3200	3.1
Brazil	3500	3.3
Others	6700	6.4
	~104,900	

jurisdictions only allow the separate reporting mineral resources as additional to ore reserves (e.g., the U.S. Securities and Exchange Commission requires mineral resources to be reported exclusive of ore reserves as 'mineralized material'). The USGS categories of reserves and reserve base are broadly similar to ore reserves and mineral resources, respectively, although this reserve base excludes inferred resources. An analysis of various mineral resource reporting codes is given by Lambert et al. (2009).

In order to assess the long-term future of Co mining (i.e., 50 to 100 years), the more realistic approach is compilation of total mineral resources as reported by various companies and mines—that is, including all measured, indicated and inferred resources. This approach is favoured here due to the fact that at many of the world's giant or long-lived Co projects, ore reserves generally represent a minority of the known geological orebody, whereas mineral resources are sufficiently understood geologically to allow long-term project planning. Over time, it is very common for mineral resources to be upgraded to ore reserves and mined. Surprisingly, it appears that there are no formal studies published on this issue (excepting a brief analysis of some Cu projects given by Mudd et al., in press). Two Co examples are:

- *Tenke Fungurume* (data from FMCG., 2007–2011)—Ore reserves in 2007 were 100 Mt of ore at 2.27% Cu and 0.33% Co containing 332 kt Co, with additional mineral resources of 127 Mt ore at 2.81% Cu and 0.30% Co containing 381 kt Co (Co recovery was expected to be 80%). In 2011, ore reserves were 141 Mt of ore at 3.00% Cu and 0.32% Co containing 455 kt Co, with additional mineral resources of 105 Mt of ore at 3.31% Cu and 0.29% Co containing 305 kt Co. Production began in 2009, and by 2011 cumulative production was 10.5 Mt ore at 3.52% Cu and ~0.4% Co with 20.4 kt Co extracted (Co recovery is ~65% but increasing gradually). A recently discovered deposit nearby at Kisanfu also has 105 Mt of ore at 2.64% Cu and 1.08% Co containing 1134 kt Co.
- *Murrin Murrin* (data from Glencore, 2012; MR, 1995–2010)—Mineral resources in 1995 were 112 Mt of ore at 1.14% Ni and 0.07% Co containing 76 kt Co. By 2011, mineral resources were 268 Mt of ore at 1.00% Ni and 0.074% Co containing 198 kt Co. Production began in 1999, and by 2011 cumulative production was ~30 Mt of ore at ~1.3% Cu and ~0.1% Co with 22.4 kt Co extracted (Co recovery is ~75%). Cumulative production plus remaining Co resources over time are shown in Fig. 3.

Clearly, for major projects such as Tenke Fungurume or Murrin Murrin, ore reserves alone do not allow a comprehensive view of recoverable Co, since over time these projects have substantially increased their resource endowment (including cumulative production). Even after allowing for the recovery rate, more recoverable Co exists in 2011 than when the projects first began development and production. For example, at Murrin Murrin, initial recoverable Co in 1995 was ~57 kt, with ~150 kt in 2011, and with 22.4 kt of Co production from 1999 to 2011, thus yielding total recoverable Co of ~172 kt—some three times the 1995 estimate.

Overall, mineral resources provide a robust basis for examining the future prospects of Co mining than ore reserves alone—demonstrating that there are sufficiently known Co resources available for several decades, with strong prospects for continued growth in recoverable Co. This approach has been demonstrated recently for Cu (Mudd et al., in press).

4.2. Quantifying economic and recoverable mineral resources

For this study, we compiled an extensive data set of Co mineral resources by individual project/deposit, as reported under a statutory resource code using 2011 data or the most recent report. Many other deposits are known to contain Co, but for these no code-based report or data exist. For some deposits, a code-based tonnage is reported but no Co ore grade, and hence other literature sources for ore grade are used in conjunction with the tonnage to estimate contained Co. Moreover, some deposits have historic mineral resources reported but these do not meet the stringent criteria of statutory resource codes. For example, numerous Ni laterite resources are given by Berger et al. (2011), many of which include Co ore grades and resource tonnages, but the current operators or owners of these resources have not publicly released code-based data on mineral resources.

Given the variable data sources and reporting, a basic data quality classification has been adopted, to indicate the approximate reliability of the mineral resource data; specifically:

- *High*—a current code-based mineral resource is reported (from 2011, but if not available, generally from within the last five years).
- *Medium*—a current code-based mineral resource is available for ore tonnage but no Co ore grade is reported and an alternate literature source is used (e.g., Berger et al., 2011, or others). These resources are similar in nature to those of existing Co mines and thus have a reasonable prospect of being considered for future extraction.
- *Low*—no current code-based mineral resource for ore tonnage or Co ore grade is reported, and alternate literature sources are used (e.g., Berger et al., 2011, or others); these resources are not considered similar in quality to those of existing Co mines, and thus are highly speculative.

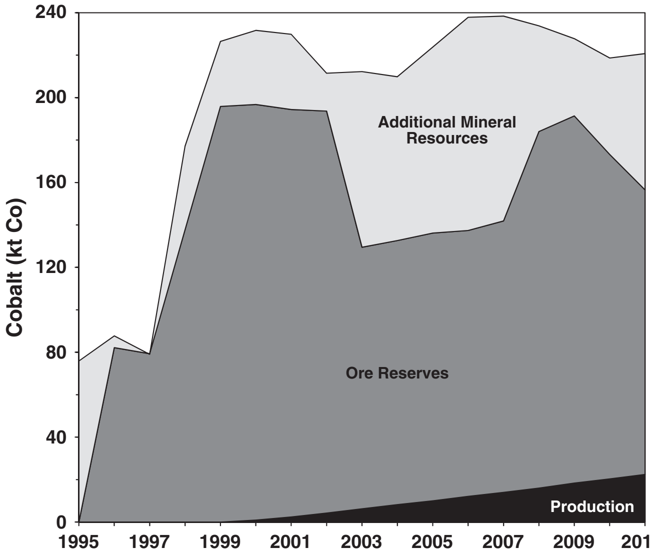

Fig. 3. Cumulative production plus remaining Co resources over time for the Murrin Murrin project, Australia (data from Glencore, 2012; MR, 1995–2010).
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The data are presented in summary form by ore type and quality (high–medium–low), with results for all deposits provided as Supplementary information. Co resources are also presented as country-based totals. For laterite resources reported as wet tonnes (e.g., several in New Caledonia and the Philippines), this was converted to dry tonnes assuming 25% moisture (data from Golightly, pers. comm.). For the recent Clarion–Clipperton resource announced by Nautilus Minerals, a value of 30% moisture is used based on dry density and porosity from Golders (2012).

For deep sea polymetallic resources, such as the Clarion–Clipperton region, they are given a low-reliability classification where a formal code-based is reported. Such resources are not given the status of high quality since there have been no projects which have gone from exploration to operations and a reconciliation performed of resource-to-reserve-to-processing conversions. As noted by Golders (2012:p. 72) for the Clarion–Clipperton region, “the potential viability of the Mineral Resources has not yet been supported by a preliminary economic assessment, a pre-feasibility study or a feasibility study”—meaning significant technical and economic uncertainty still remains in the development of deep sea mining ventures. Given the importance of resource-to-reserve conversions and reconciliation in statutory codes, the allocation of low quality status to such mineral resources is conservative.

A small number of Co-containing deposits are known to be missing from the dataset, principally due to a lack of public reporting (and perhaps language barriers). This situation is common for government-owned enterprises, especially in developing countries, but the resource data remain elusive for this study, effectively leaving some Co resources unquantified. The results from this research therefore should be regarded as minimum estimates.

A typical recovery rate is applied to each deposit based on ore type using an approximate average from Table 1, since the same ore types tend to use very similar processing technology. The actual extent of Co recovery over time, of course, will continue to depend on economics (supply/demand, prices, input prices, etc.), processing technology, environmental and social constraints, and so on.

The methodology adopted herein allows a more comprehensive picture of potentially recoverable Co beyond the current constraints of code-based reporting. Assessing the supply and demand of Co resources is important to enable the identification of any changes that may have significant repercussions for the global economy, technology needs and the environment.

5. Results and discussion

5.1. Global contained and recoverable cobalt resources

A division of contained and recoverable Co resources by data quality and ore type is provided in Tables 3 and 4, respectively. The combined total is ~26.79 Mt of contained Co from 307 projects, with 15.21, 5.61, and 5.98 Mt of contained Co in the high, medium and low reliability categories, respectively (219, 76, and 12 deposits, respectively). In terms of ore types, some 8.59, 8.57, 6.75 and 1.81 Mt Co are in stratiform sediment-hosted, laterite, IOCG and magmatic sulfide deposits, respectively (46, 146, 27 and 58 deposits, respectively), with 0.33 Mt Co in all other deposit types (30 deposits). Data for all deposits are plotted on a tonnage-grade graph in Fig. 4. A comparison of Co resources by country based on USGS data and this study is given in Table 5; USGS data for reserves and reserve base over time for USA and the world, as well as national estimates over time for China and Australia, are shown in Fig. 5. Applying typical recovery rates for different ore types gives ~15.9 Mt of Co recoverable, with ~10.7, ~2.64 and ~2.63 Mt of Co recoverable in high, medium and low quality resources, respectively (Tables 3 to 5).

Cobalt resources in major mining countries with high-reliability data (i.e., formal mineral resource reporting) significantly exceeds the USGS reserves estimate for all countries except Russia and New Caledonia. For example, the USGS reserves estimate for Australia is 1400 kt Co, whereas Geoscience Australia's estimate is 2984 kt Co (GA, 2012); this study indicates a total of 6252 kt Co. Our compiled data indicate that 3759 kt Co exists in IOCG deposits within Australia, including 3633 kt Co in Olympic Dam and Oak Dam East (both low-reliability resource estimates), with 1969 kt Co occurring in Ni–Co laterites, 271 kt Co in magmatic sulfides and 253 kt Co in all other deposit types. If the low-reliability Olympic Dam and Oak Dam East resources are excluded, the remainder of Australia's Co resources are dominated by Ni–Co laterites. China is reported to have 682 kt of Co resources (Hongtao et al., 2011), whereas our compiled data indicate 140 kt Co (all medium reliability), suggesting an additional 542 kt Co resources are not included in our estimate.

Table 3
Contained and recoverable Co resources ranked by reliability.

	High	Medium	Low	All deposits
Total contained cobalt (kt Co)	15,207.1	5607.7	5977.7	26,793
Count (number of deposits)	219	76	12	307
Weighted average ore grade (% Co)	0.070	0.096	0.050	0.069
Standard deviation of ore grade (% Co)	0.182	0.065	0.198	0.165
Minimum ore grade (% Co)	0.006	0.011	0.010	0.006
Maximum ore grade (% Co)	1.32	0.43	0.74	1.32
Total recoverable cobalt (kt Co)	10,661	2637	2627	15,918
Proportion of recoverable cobalt (%)	66.95	16.56	16.49	

For many countries, the current estimate reported in this study is likely to be greatly underestimated for several reasons: (1) Co grades are not reported for many deposit types that are known to contain Co (especially laterite-rich countries), (2) ongoing exploration is continuing to find major new deposits (e.g., Sulawesi in Indonesia, Voisey's Bay in Canada, Kisanfu in the DRC) or expand resources at current projects (e.g., Murrin Murrin, Australia), (3) changing/improving processing technology and increased demand for Co are leading to increased recovery of Co from existing deposits, and (4) some countries (e.g., China) do not publicly report any data on Co deposits. Although numerous Co deposits are known in China (e.g., Feng and Zhang, 2004; Xu and Zhu, 2000), the fact that China does not require detailed public reporting (as per most statutory codes) means that the available information is often old or incomplete (e.g., kt Co only, and not detailed by deposit type). In addition, if a different processing configuration was adopted for some projects, Co could be recovered, or recovered at much greater efficiency. For example, most RKEF plants do not target Co recovery, but if an HPAL plant is used, Co is much more critical to the project's economic success and generally would be recovered and reported (e.g., Murrin Murrin, Australia). A new approach that shows promise for processing laterites is heap leaching, which recently moved into commercial production at Murrin Murrin in Australia (Readett and Fox, 2010) and is being investigated at pilot scale for numerous projects globally (e.g., Çaldag in Turkey). If heap leaching proves successful, it could provide a new option for developing Ni–Co laterite projects at lower unit capital and operating costs, although caution is warranted given the difficulties involved in the mining of laterites.

The Ni–Co laterite resource data reported by Berger et al. (2011) are generally larger, often significantly, than the mineral resource reported by the operating company of a given project. For example, Sherritt International Corporation's Moa Bay joint venture in Cuba in 2011 reported reserves of 66.6 Mt of ore at 1.26% Ni and 0.13% Co (Beaton et al., 2011), while Berger et al. (2011) use a much larger resource of 290 Mt of ore at 1.27% Ni and 0.13% Co (this is stated as a pre-mining geological estimate). This difference mainly reflects the preference for resource data showing the full known extent of

Table 4
Contained and recoverable Co resources by ore type.

		Strat. sed.-hosted	Laterite	IOCG	Magmatic sulfide	VMS	Chem. prec.—on land	Chem. prec.—deep sea	Miscellaneous[a]	All deposits
Total contained cobalt (kt Co)		8593.2	8571.6	6746.2	1811.4	193.9	3.6	739.2	133.4	26,793
Count (number of deposits)		46	146	27	58	20	3	1	6	307
Ore grade	Weighted average (% Co)	0.154	0.074	0.060	0.019	0.023	0.111	0.240	0.045	0.069
	Standard deviation (% Co)	0.317	0.030	0.101	0.048	0.062	0.086	–	0.311	0.098
	Minimum (% Co)	0.010	0.024	0.008	0.006	0.010	0.011	0.240	0.010	0.006
	Maximum (% Co)	1.32	0.227	0.43	0.27	0.24	0.18	0.24	0.74	1.080
Typical Co recovery rate (%)		**70%**	**75%**	**25%**	**60%**	**60%**	**80%**	**70%**	**25–80%**	
Total recoverable cobalt (kt Co)		**6015**	**6429**	**1687**	**1087**	**116**	**2.9**	**517**	**70.8**	**15,925**
Resource proportion (%)		**37.8**	**40.4**	**10.6**	**6.8**	**0.73**	**0.02**	**3.2**	**0.44**	**100**

[a] Miscellaneous includes porphyry, skarn, polymetallic unconformity U and vein/replacement deposit types.

the geological mineralization, which is uniformly larger than the ore reserve or mineral resource due to paucity of information. Over time, as mining proceeds, further work is undertaken to convert geological mineralization into a mineral resource and then into an ore reserve, but this conversion takes time and funding, and typically is only done as required for mine planning or approval purposes (some countries also tax ore reserves and not mineral resources). The Berger et al. (2011) study also includes cumulative production for the total resource (where available), which for some older projects is substantial and can equal or exceed remaining resources. As discussed earlier, it is common for projects to continue to increase mineral resources over time as development and mining proceeds, and so it therefore is reasonable to include such estimates in our study where no other data exist, with such resources given a medium reliability classification.

Overall, the data compiled in this study demonstrates a sound methodology for estimating recoverable Co resources as of 2011. The 15.21 Mt of contained Co in high reliability resources, excluding the 5.61 and 5.98 Mt of Co in medium and low reliability resources, respectively, clearly represents a minimum value that is likely to continue growing as new projects are discovered and developed, resources at existing projects are expanded, and as processing configurations change to facilitate greater recovery of Co (especially for Ni–Co laterite ores).

5.2. Future prospects for cobalt resources

At 2011 global production rates of ~109 kt Co/year, our recoverable resource estimate yields ~146 years at constant production. This estimate suggests that, even allowing for a doubling of annual production and modest recovery rates, economically recoverable Co resources will remain adequate for several decades, at least. Over this time frame, a range of other factors will become increasingly important, including (Ali and Grewal, 2006; Eckelman, 2010; Mudd, 2010b):

- The cost of energy and associated greenhouse gas emissions (especially given that the mineral processing involved in Ni–Co laterite projects is much more energy-intensive than sulfide ore processing).

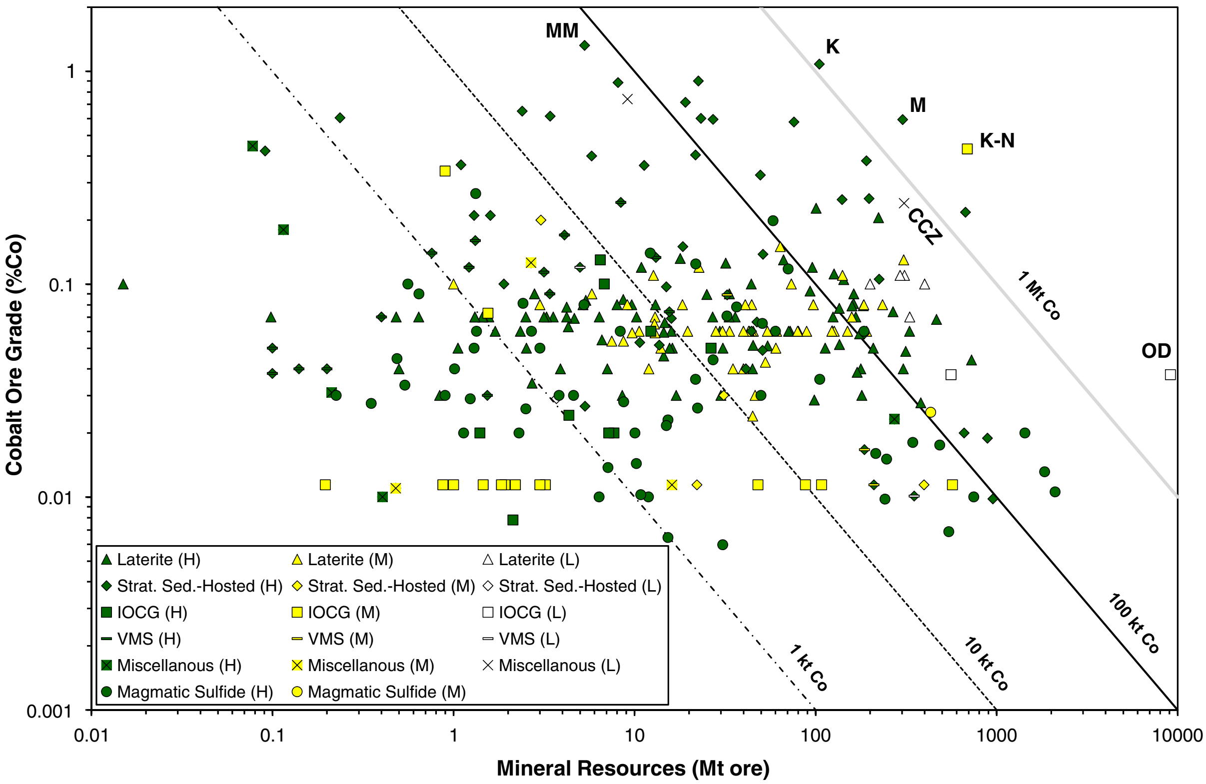

Fig. 4. Cobalt resources by ore type and reliability (Note, for reliability: green is high, yellow is medium, white is low; H is high, M is medium and L is low reliability; Miscellaneous includes porphyry, skarn, polymetallic unconformity U, vein/replacement and chemical precipitate deposit types; OD—Olympic Dam, K-N—Konkola-Nchanga, M—Mutanda, K—Kisanfu, MM—Mutondo Mountain, CCZ—Clarion–Clipperton Zone).

Table 5
Co reserves-resources (kt Co) by country (2011) (USGS reserves data from USGS, 2012).

Country	USGS reserves	USGS reserve base (2008)[b]	National estimate	This study	
				Contained	Recoverable
Dem. Rep. Congo	3400	4700[a]		7666.3	5366.4
Australia	1400	1800	2984[c]	6251.7	2722.6
Zambia	270	680		3426.9	1060.2
Cuba	500	1800		1027.6	770.7
Indonesia				916.5	687.4
Brazil	89[d]	40[d]		854.2	635.0
Tonga				739.2	517.4
Cameroon				684.9	513.7
Canada	150	350		660.0	395.6
Philippines				677.2	507.9
USA	33	860		454.7	276.1
New Caledonia	370	860		353.9	265.4
Papua New Guinea				384.2	288.1
Finland				347.8	227.2
Cote d'Ivoire				322.3	241.7
Columbia				231.7	173.8
Russia	250	350		227.4	152.6
Madagascar				190.3	142.7
Burundi				175.9	131.9
Tanzania				206.0	136.3
India			[e]	143.3	107.5
China	80	470	682[f]	140.3	84.9
Solomon Islands				126.6	95.0
Guatemala				93.8	70.3
Kazakhstan				75.9	57.0
Morocco	20			67.7	54.2
Puerto Rico				62.8	47.1
South Africa				62.2	37.3
Dominican Republic				47.8	35.8
Sweden				36.8	22.1
Portugal				31.1	18.7
Macedonia				25.8	19.4
Turkey				25.2	18.9
Uganda				13.0	7.8
Kosovo				11.7	8.8
Serbia				9.4	7.1
Vietnam				7.8	4.7
Venezuela				4.8	3.6
Norway				4.0	2.4
Malawi				2.6	1.9
Argentina				1.4	0.8
Other	990	1100			
Total	**7500**	**13,000**		**26,793**	**~15,900**

Notes:

[a] The last year the USGS reported reserve base was for 2008 (USGS, 2009).

[b] The USGS reserves are strictly ore reserves only, while reserves base only include measured and indicated resources (and exclude inferred mineral resources).

[c] Australia's reported economic resources were 1191 kt Co while economic and sub-economic resources were 2984 kt Co (GA, 2012).

[d] For Brazil, the USGS reported reserves of 29 kt Co in 2008 and 40 kt Co as reserve base.

[e] India report total Co *ore resources* of 44.9 Mt ore but give no grade or ore types (IBM, 2011).

[f] From Hongtao et al. (2011).

- Co-dominant projects are often arsenic rich (e.g. Bou Azzer in Morocco, Ahmed et al., 2009; Blackbird in USA, Slack, 2012), leading to significant environmental challenges.
- Land use conflicts, especially potential and perceived impacts of mine waste disposal and management on land values.
- Water consumption and water resources management, particularly concerning potential and perceived impacts of mine waste disposal and management.
- Royalty flows and economic benefit sharing, especially in developing economies such as New Caledonia or in southern Africa.
- Improvements in recycling, and whether this could become competitive with new mine supply in volume, costs and environmental impacts—at present, very little Co is recycled and most is discarded to landfills (Harper et al., 2012).

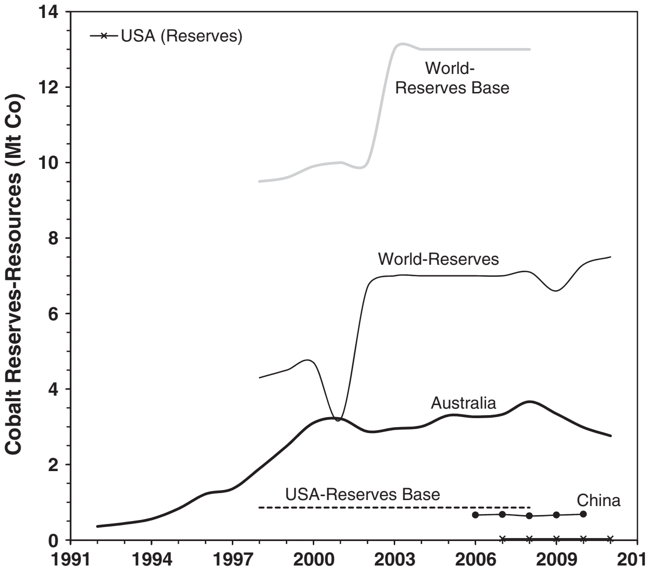

Fig. 5. Reserves and resources over time for Australia (GA, 1992–2011), China (Hongtao et al., 2011), USA and world (USGS, 1996–2011).

There are two other major potential Co resources which have not been included in this study: Co in Fe–Mn nodules and crusts on the ocean floor and seamounts (ore type 7 above, with the recent Clarion–Clipperton resource estimate being the exception, as discussed below), and Co contained in mine tailings or smelter slags. In addition, some known major Co deposits are located in regions now declared as national parks and are thus excluded from our study (e.g., Windy Craggy in British Columbia, Canada, with 297 Mt ore at 1.38% Cu and 0.08% Co for 238 kt Co; Peter and Scott, 1999).

For ocean Fe–Mn nodules and crusts, estimates of the potential Co resource vary widely, largely due to limited data on size, tonnage, and Co concentrations. The data for some sites include:

- La Victoria Knoll, 72 km from the coast of Baja California, Mexico, where Co concentrations average 713 mg/kg (Hein et al., 2005).
- Marshall Islands, central Pacific Ocean, where Co concentrations average 5500 mg/kg (Hein et al., 1988).
- Fort Payne, Tennessee, where Co concentrations average 8500 mg/kg (Larson, 1970).
- Portugese Economic Exclusion Zone, northeast Atlantic Ocean, where Co concentrations average about 4000 mg/kg (Muiños et al., 2013).
- Shatsky Rise, northwest Pacific Ocean, where Co concentrations average about 2000 mg/kg (Hein et al., 2012).

Estimates of the potential Co mass in Fe–Mn nodules and crusts ranges from 39.3 Mt Co in the western Pacific Ocean (Clark et al., 1985), to 134.0 Mt Co in the Clarion–Clipperton region of the western Pacific Ocean (ISA, 2010), 0.2 Mt Co in a small region of the central Indian Ocean (Sharma, 2011), and to global estimates of 60 Mt Co (Archer, 1979). According to Archer (1981), the estimated mass of seafloor nodules globally is about 350,000 Mt (dry), although only a small fraction of these nodules would likely meet conceivable economic criteria for mining (such as combined Ni–Cu–Co ore grades, ore thickness, water depth), meaning that the total recoverable Co resources are likely to be in the range of 25 to 40 Mt Co (depending on economic and mining criteria). A recent estimate by Hein et al. (2013) suggests that 44 Mt Co is present in nodules from the Clarion–Clipperton area and a further 50 Mt Co in the Prime Crust Zone in the western Pacific. These various estimates are geologic endowment and cannot be considered a formal mineral resource, and are thus excluded from our dataset.

The past decade has seen a surge of interest in assessing the potential for deep-sea mining, reflecting the recent estimate (Hein et al., 2013) that potentially recoverable Co from deep-sea deposits may exceed that in terrestrial deposits. In fact, a number of prospective seafloor mining projects are under review, although many engineering and environmental challenges remain to be addressed (e.g., Hein et al., 2013; Woodwell, 2011). However, given the fact that formal mineral resource codes are not readily applicable to estimating economic mineral resources in seafloor mining projects, it is speculative to predict to what extent any (*if any*) of the above estimates may become realistically mineable resources in the future (i.e., still no commercially successful projects operating as of early 2013).

The most prospective deep sea mining project worldwide is Solwara in Papua New Guinea (PNG), where Nautilus Minerals received approval from the PNG government in January 2011 to mine hydrothermal sulfide deposits in the Bismarck Sea, New Ireland province, at a water depth of 1.6 km. The Solwara 1 and 12 resources are very small but high grade (2.8 Mt of ore at 7.7% Cu, 5.7 g/t Au, 32 g/t Ag and 0.9% Zn) (NM, 2011); no Co grades are reported.

In September 2012, the first-ever, code-based estimate (using NI 43-101) for the Clarion–Clipperton zone was announced by Nautilus Minerals, who reported 440 Mt of wet ore at 26.9% Mn, 1.2% Ni, 0.24% Co and 1.1% Cu—containing ~739 kt Co (based on 30% moisture in ore) (Golders, 2012). This shows that the larger seafloor metal resources are in Fe–Mn nodules and crusts and not in sulfide deposits. In the north-east Atlantic, (Muiños et al., 2013) present an estimate of Co-rich seafloor mounts in the greater Madeira-Tore Rise (MTR) region west of Portugal, with the Nameless and Unicorn deposits containing 71 and 130 Mt of wet ore at a grade of ~0.34% Co and containing a reported 240 and 450 kt Co, respectively. The whole MTR region was estimated to host 1100 Mt of wet ore at the same grade and reportedly containing 3800 kt Co. However, given that the data used to derive these estimates is somewhat sparse and significantly lower than the normal requirements for a code-based estimate, we have excluded these MTR sites from our data compilation. It should also be noted that (Muiños et al., 2013) acknowledge that considerably more work is required to establish a mineable resource in this area, although we have included the Clarion–Clipperton zone as a low reliability resource as it is a formal code-based estimate. Despite the hype and optimism, deep sea mining has yet to produce a viable commercial operation.

There are significant community and scientific concerns about the potential impacts on ecology and biodiversity from prospective deep sea mining projects, especially given the uniqueness of the chemosynthetic biodiversity and the interactions among near-surface species and those living in deep waters (ISA, 2007, 2011; UN-DOALS and ISA, 2004). The Solwara project is yet to begin production and remains delayed due to a commercial dispute between Nautilus Minerals and the PNG government (the 30% joint venture partner in Solwara), demonstrating the combination of technical, financial, social and environmental risks involved with such a pioneering effort.

Mine tailings and smelter slags are additional potential future Co sources. Among mines in the central African Cu-belt, the Co extraction efficiency varies widely, and with ore grades up to 1% Co, an inefficient extraction process can leave as much Co in the mine tailings as in current mineral deposits, i.e., 0.2 to 0.7% Co. In addition, the Sudbury Ni–Cu field, by 2011, had processed ~981 Mt of ore and produced more than 50 kt Co (Co production data are incomplete and could be as high as 100 kt Co; data updated from Mudd, 2010b), with the large amount of tailings in this area containing grades up to ~0.02% Co (Peek et al., 2011; Perederiy et al., 2011). Two other examples are the ~1.6 Mt of polymetallic U–Cu–Ni–Co–Ag tailings at Eldorado-Port Radium in Canada, and the ~18.5 Mt of Cu–Co tailings at Kakanda in the DRC; both sites are being actively assessed for re-processing. Smelter slags could be much higher in Co grade than ores (up to a few percent; see Perederiy et al., 2011; Vítkova et al., 2010), although at present the only known Co project using tailings as the sole feedstock is Kilembe in Uganda. Some PGE tailings or smelter slags are re-processed but this is mainly for PGEs and not Ni–Cu–Co (Glaister and Mudd, 2010). Recovery of Co from tailings or slag would invariably depend on the economics of the primary metal, such as Cu, Ni or PGEs, and the relative costs versus those of existing mining projects. The future potential for tailings as a mineral resource is recognised in some mining sectors, at least at a policy level, such as Australia (Minns, 2007) where many gold tailings are re-processed (Mudd, 2007). At present, it would appear that new mines are the more economic Co source, but tailings and smelter slags likely represent a potentially growing and readily available Co resource in the future.

For this study, we have not included any Co resources from seafloor nodules and crusts (except for the two on land reported in China and the recent Clarion–Clipperton resource estimate), mine tailings or smelter slags (except for the very few being assessed for development), in view of data limitations and uncertainty. In the distant future, however, as technology improves and terrestrial deposits become depleted, the economics and viability of these speculative resources may change accordingly.

6. Summary and conclusions

This study has compiled an extensive data set on global cobalt resources, using a hybrid mineral resource accounting methodology to estimate the global contained and recoverable resources of a major by-product or companion metal such as cobalt. Our results indicate significant known Co resources, with amounts of contained Co being about 26.8 Mt and recoverable Co being about ~15.9 Mt, with the clear majority of Co occurring in resources assessed as high quality.

The research reported and discussed demonstrates that previous estimates of the recoverable Co resources are significantly lower than is the actual amount. Monitoring the supply and demand of these resources is important to enable the identification of any changes that may have significant repercussions for the global economy, technology needs and the environment. From the perspective of the resource itself (although not necessarily from that of energy supply or environmental or social issues), there appears to be no geological shortage of recoverable Co, on a global basis, for at least several decades.

In addition to evaluating cobalt's supply situation, this research demonstrates a workable approach to estimating the resources of companion metals in general. Many of these metals are crucial ingredients for a number of modern technologies, yet their geological abundance in ore deposits has not been adequately reported. With the methodology described herein, this lack of information can be addressed, at least in approximate fashion. We anticipate further work to derive recoverable resource values for a number of other companion metals, in order to better inform potential users of their geological occurrence and abundance and therefore the sustainability of companion metals in a variety of modern uses, especially environmentally-focussed technologies such renewable energy and consumer electronics.

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