BGS COMMODITY REVIEW

Cobalt

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Cover photograph: Kevitsa, Auroras on Vajunen reservoir.
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General characteristics

Cobalt is a lustrous, greyish-silver, brittle metal. It is very hard and tough, and can take a high polish. It retains its strength at high temperatures and has fairly low thermal and electrical conductivity, a high melting point and multiple valences. Cobalt is ferromagnetic and is therefore capable of being magnetised. Other important useful properties are its ability to form alloys with many other metals (e.g. chromium, molybdenum, nickel) and to maintain its magnetic properties at high temperatures (up to 1121°C). Other physical characteristics are summarised in Table 1.

Table 1 Selected physical properties of cobalt (Data sources: MMTA (2016); Wolfram Research Inc (2019)).

Property	Value	Units
Symbol	Co	
Atomic number	27	
Atomic weight	58.93	
Density at 25 °C	8900	kg/m^3
Melting point	1495	°C
Boiling point	2870	°C
Hardness	5.0 – 5.5	Mohs scale
Electrical conductivity	1.7×10^7	S/m
Thermal conductivity	100	W/(m°C)

Mineralogy

The earth's continental crust has a cobalt concentration ranging from 15 to 30 parts per million (ppm) (Roberts & Gunn, 2014). Ultramafic igneous rocks like dunite and serpentinite have average cobalt concentrations between 109 and 115 ppm, while mafic igneous rocks such as basalt contain about 47 ppm cobalt (Slack et al., 2017). Although pure cobalt is not found in nature, approximately 30 cobalt-bearing minerals are known, many of which are widespread. It is preferentially bound to iron, nickel, copper and sulfur rather than to oxygen, forming various sulfide and sulfarsenide phases e.g. cobaltite, carrollite, skutterudite, erythrite (Figure 1; Table 2). However, it also forms oxides, hydroxides and carbonates. Nickel-copper sulfide ores like pentlandite, pyrrhotite and chalcopyrite in magmatic nickel-copper(cobalt-PGE) deposits may reach cobalt grades between 0.4 and 1.3% (Roberts & Gunn, 2014). Cobalt in nickel-cobalt laterites is enriched in oxides (goethite, hematite, asbolane, lithiophorite and heterogenite), manganese-oxides and oxyhydroxides (Marsh et al., 2013).

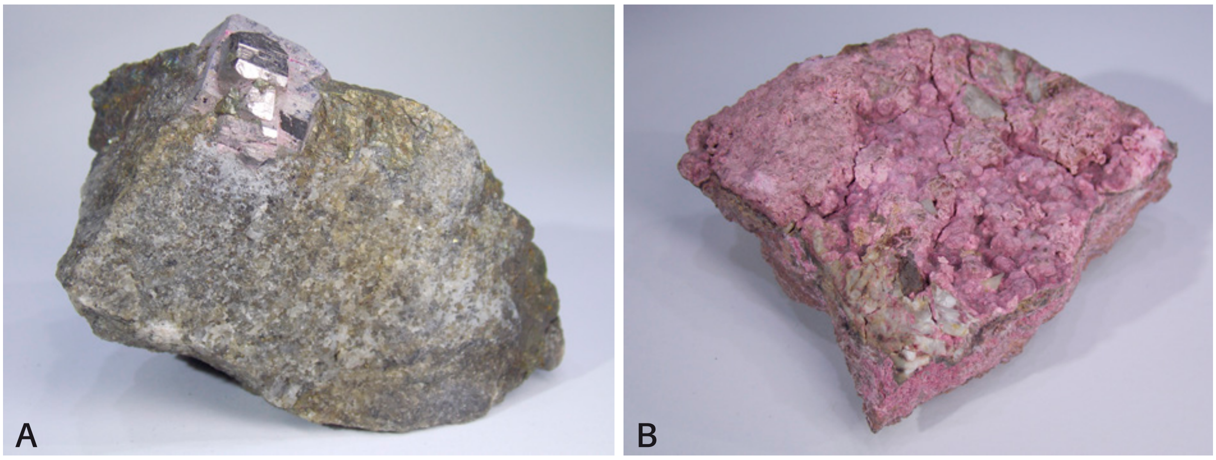


Figure 1 **A**. Cobaltite (unknown location; maximum dimension of specimen 8 centimetres). **B**. Erythrite, from Hesse, Germany, (maximum dimension of specimen 8 centimetres). (Photos provided by Camborne School of Mines, University of Exeter, (2019)).

Table 2 Common cobalt-bearing minerals (Data sources: Barthelmy (2014); Broughton (2014)).

Mineral name	Chemical formula	Cobalt content (weight %)	Selected occurrences
Carrolite	$Cu(Co,Ni)_2S_4$	28.56	Chambishi, Copperbelt, Zambia; Carroll County, Maryland, USA
Cattierite	CoS_2	47.89	Kambove District, Katanga (Shaba), DRC
Cobaltite	CoAsS	35.52	Sudbury, Canada; Broken Hill, New South Wales, Australia
Erythrite	$Co_3(AsO_4)_2{\cdot}8H_2O$	29.53	Daniel Mine, Germany; Bou Azzer, Morroco
Glaucodot	(Co,Fe)AsS	26.76	Hakansboda, Vastmanland, Sweden
Heterogenite	CoOOH	64.10	Katanga Copperbelt, DRC
Kolwezite	$(Cu,Co)_2(CO_3)(OH)_2$	17.84	Kolwezi, Kolwezi District, Katanga (Shaba), DRC
Linnaeite	$Co^{2+}Co_2^{3+}S_4$	57.95	Bastnäs mines, Riddarhyttan, Västmanland, Sweden
Safflorite	$(Co,Ni,Fe)As_2$	21.25	Daniel Mine, Germany
Skutterudite	$(Co,Ni)As_{3-x}$	17.95	Skutterud Mines, Norway; Bou Azzer, Morroco
Willyamite	(Co,Ni)SbS	20.78	Broken Hill, Australia

Deposit types

Most cobalt is recovered as a by-product of copper or nickel mining (Hitzman et al., 2017; Mudd et al., 2013) (Figure 2). The major cobalt-producing regions are the Democratic Republic of Congo (DRC) and Zambia, with some large deposits also known in Australia, Russia, Cuba, New Caledonia and Canada (Table 3, Figure 6). Cobalt can be found in economic concentrations in three principal deposit types: stratiform sediment-hosted copper-cobalt deposits; nickel-cobalt laterite deposits; and magmatic nickel-copper (-cobalt-platinum-group element (PGE)) sulfide deposits (Mudd et al., 2013; Naldrett, 2004). Cobalt is also concentrated in a variety of other geological settings and deposit types, from some of which it was extracted in the past (Slack et al., 2017). Significant concentrations of cobalt may also occur on the sea floor in iron-manganese-rich nodules and cobalt-rich crusts, although to date no cobalt has been commercially extracted from these.

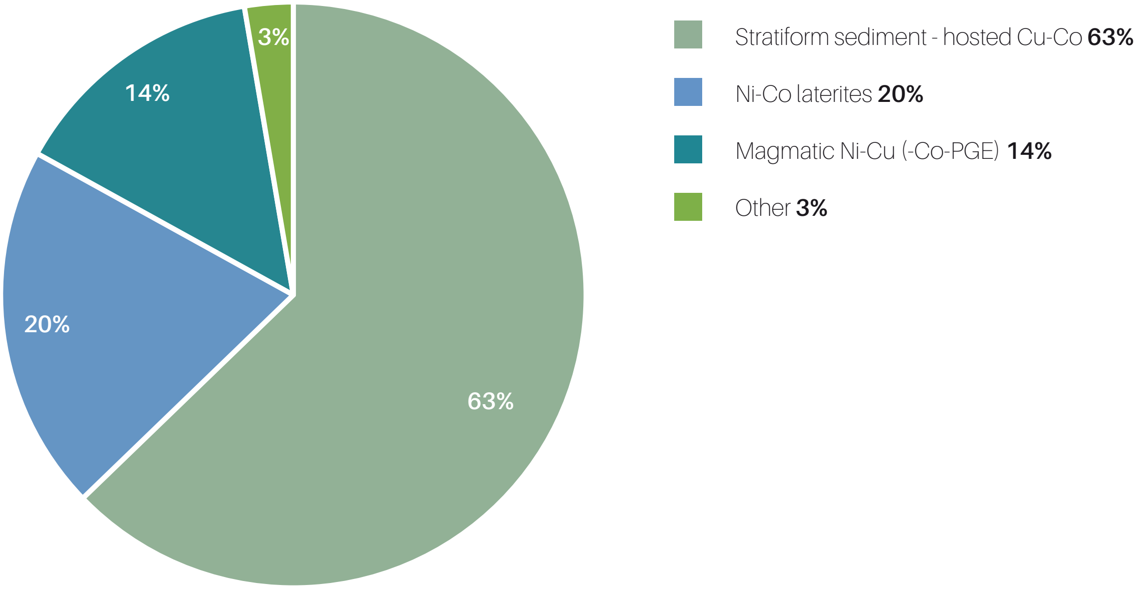


Figure 2 Approximate breakdown of cobalt mine production by deposit type in 2017 (Data source: British Geological Survey World Mineral Statistics Database). VMS = Volcanogenic massive sulfide.

Stratiform sediment-hosted copper-cobalt deposits

This class of deposits, also termed 'sediment-hosted copper' (Cox & Singer, 1986) or 'sediment-hosted stratabound copper' (Taylor et al., 2013), is not only the world's second largest source of copper, after porphyry deposits, but is also the most important source of cobalt accounting for 66 per cent of global cobalt mine production in 2017 (Brown et al., 2019; Hitzman et al., 2017). The deposits typically comprise thin (commonly less than three metres) sulfide-bearing zones more or less concordant with the lithological layering in the host siliciclastic or dolomitic sedimentary rocks. The main copper ore minerals are chalcocite, bornite and chalcopyrite, with carrolite the most important cobalt-bearing mineral. Numerous models have been proposed to explain the formation of these deposits: some emphasise the dominance of syngenetic and diagenetic processes during early basin evolution, while others stress the importance of hydrothermal processes during basin inversion (Annels, 1986; Cailteux et al., 2005; McGowan et al., 2006; McGowan et al., 2003). The current consensus is that metalliferous saline hydrothermal fluids entered at low to moderate temperatures during diagenesis and the early stages of deformation and metamorphism (Slack et al., 2017; Zientek, 2012). While sediment-hosted copper deposits are widespread, large deposits are recognised in only three basins worldwide, of which the Neoproterozoic basin of central Africa and the Permian Zechstein basin of northern Europe are most important (Hitzman et al., 2005; Hitzman et al., 2010). Significant quantities of cobalt are known to be present in the Central African Copperbelt (CACB).

The CACB, located in the Katanga Province of southern DRC and in north-western Zambia, hosts one of the world's greatest concentrations of copper and cobalt deposits (Selley et al., 2005; Taylor et al., 2013) (e.g. Figure 3).

Figure 3 Central north-west open pit of the Mutanda copper-cobalt deposit, near Kolwezi, Lualaba Province, DRC. (Photo courtesy of Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (2019)).

The Zambian Copperbelt (ZCB) and the Congo Copperbelt (CCB) are geographically distinct copper provinces. The ZCB has fewer deposits but contains most of the 'giant' deposits (i.e. those containing more than two million tonnes of copper metal). Accordingly, the ZCB hosts about 60 per cent of the copper endowment of the CACB, while the CCB has many small, but fewer giant deposits, accounting for approximately 40 per cent copper endowment (Theron, 2013). The largest and richest cobalt endowments are located mostly in the western part of the CCB, with Co grades of 1.1% in the Kisanfu deposit, 0.7% at Mukondo and 0.6% at Tilwezembe (Hitzman et al., 2017). In the ZCB cobalt grades are generally lower (e.g. 0.4% at Nchanga and 0.1% at Nkana), but, because these deposits are very large, their cobalt endowment is substantial (Hitzman et al., 2017). There is no consensus on the processes responsible for the formation of the CACB or for its cobalt endowment. Theron (2013) points to the strong sedimentological and lithological control on the distribution of these deposits. His model involves the reduction of evaporitic sulfates giving rise to reduced H_2S- and CO_2-bearing pore fluids in the host rocks. These were subsequently mixed with oxidising copper-cobalt-bearing brines derived from the underlying footwall rocks at low temperatures ranging from 100–200°C. Later remobilisation of the mineralisation took place at higher temperatures during metamorphism and tectonism related to the Lufilian orogeny.

The metal source in the CACB deposits is not well constrained. Theron (2013) points out that the underlying basement rocks are alkali granite/granitoids possibly similar to these hosting the iron oxide-copper-gold (IOCG) deposits at Ernest Henry and Olympic Dam in South Australia with a significant cobalt enrichment. In contrast, Hitzman et al. (2017) note the abundance of mafic intrusions in the western sector of the ZCB where cobalt is extracted as a by-product. The importance of these intrusions as a potential source of cobalt remains unproven. Other authors stress the importance of tectonics in a protracted history of ore deposition in the CACB. The major significance of faults reactivated during basin inversion has been proposed at Nchanga in Zambia (McGowan et al., 2006), while structures developed during the Lufilian orogeny were shown to be important in late-stage mineralisation and/or remobilisation of high-grade ores at Nkana, Zambia (Muchez et al., 2010). The post-orogenic history is also important in the development of cobalt ores in the CACB. Intense oxidation, commonly down to a depth of 100 metres, led to partial oxidation and leaching of metals in sulfide ores. At some localities in the DRC (e.g. Tenke Fungurume and Musonoi) this led to the development of cobalt enrichment in the upper part of the oxidised zone to form a 'cobalt cap'. At the same time copper was removed from this zone by meteoric waters. At the Musonoi deposit exploitation of the well-developed 'cobalt cap' began in 1940/41, while the mine itself did not begin operation until 1945. Another example is the upper zone of the Oliveira fragment in the KOV (Kamoto-Oliveira-Virgule) deposit which has a superficial enrichment of cobalt, while copper has been entirely leached (Gauthier & Deliens, 1999).

The largest sediment-hosted stratiform copper deposit in the world is located on the southern flank of the Permian Zechstein Basin at Lubin-Sieroszowice in south-west Poland. Taylor et al. (2013) report a deposit tonnage of 3612.5 million tonnes of ore grading 1.99% Cu and 56.5 ppm Ag, giving about 72 million tonnes of contained copper metal. No cobalt data are provided for this deposit by Taylor et al. (2013), but Pazik et al. (2016) reported cobalt concentrations of 140 ppm in the Lubin ore. The world's largest cobalt resource is located in the Kamoto-KOV-Musonie-Mupine deposit which contains 416.2 million tonnes of ore grading at 4.49% Cu and 0.39% Co (Taylor et al., 2013). These authors report median Co concentrations of 0.3% in 170 sediment-hosted stratiform deposits worldwide, with a median of 0.4% cobalt in reduced facies deposits from the DRC.

Nickel-cobalt laterite deposits

Laterites are regoliths that develop in humid tropical climates during the weathering of various lithologies (Butt & Cluzel, 2013; Freyssinet et al., 2005; Slack et al., 2017). Nickel laterite deposits account for 72 per cent of global nickel resources in 2010 and about 60 per cent of the global nickel production in 2017 (Brown et al., 2019). Where they are developed over ultramafic rocks they may also contain appreciable concentrations of cobalt at grades between 0.025% and 0.18%, which accompany nickel values that generally exceed 1% in mined deposits (Berger et al., 2011; Slack et al., 2017). Nickel-cobalt laterites locally contain abundant scandium and, rarely, elevated concentrations of PGE. The ore zones are generally in the range of 10–40 metres thick. The most important ore minerals include serpentine, talc, chlorite, clays, erythrite, heterogenite, asbolane, heazlewoodite, millerite, goethite, limonite and lithiophorite (Slack et al., 2017). Most nickel-cobalt laterite deposits form by the weathering of ophiolites and are found within accretionary terranes (Freyssinet et al., 2005). The deposits are mostly mid-Tertiary to Holocene in age.

Metal accumulation in laterites involves various supergene processes and depends on several geological variables including protolith composition, topography and structural preparation. Climate history is also a major control on nickel laterite formation as relatively high temperatures accompanied by high rainfall facilitate intense weathering of ultramafic protoliths. Recent data suggest that the majority of peridotites presently weathering to form nickel-cobalt laterites experience distinct climatic conditions characterised by limited seasonality and annual precipitation of more than 1000 millimetres (Thorne et al., 2012). Another important factor in forming nickel-copper lateritic regolith deposits is the degree of permeability of the parent material (Brand, 1998; Pelletier, 1996). Faults, fractures, joints and cleavage play a key role in nickel-cobalt lateritic regolith mineralisation by increasing the permeability of the protolith.

Three nickel-cobalt laterite deposit sub-types are recognised: (1) clay silicate; (2) hydrous magnesium silicate; and (3) iron oxide – limonite deposits (Freyssinet et al., 2005; Gleeson et al., 2003). Clay-rich nickel-cobalt laterites mainly occur in semi-arid regions, while most hydrous silicate-rich deposits develop in humid climates. Oxide-dominant deposits form in a range of climatic conditions.

The Kalgoorlie and the Murrin Murrin deposits in Western Australia (Gaudin et al., 2005) and the Goro deposit in New Caledonia (Wells et al., 2009) are examples of some of the world's many large nickel-cobalt laterite deposits. Resources, reserves and past production amount to 727 million tonnes grading 0.044% Co in the Kalgoorlie district, 231 million tonnes grading 0.076% Co at Murrin Murrin and 323 million tonnes grading 0.11% Co at Goro (Slack et al., 2017; Glencore, 2018a) (Table 3). The manganiferous Nkamouna cobalt-nickel deposit in Cameroon, which has not yet been worked, is one of the few in which cobalt would be the principal economic metal to be mined (Dzemua & Gleeson, 2012). In 2011, reported NI 43-101 compliant proven and probable ore reserves in this and the nearby Mada deposit were 68.1 million tonnes grading 0.26% Co, 1.48% Mn and 0.66% Ni (SRK Consulting, 2011). This represents possibly one of the largest undeveloped cobalt deposits in the world. Other large nickel-cobalt laterite deposits include Jacare and Niquelandia in Brazil, Moa and Nicaro in Cuba, and Acoje, Coral Bay and Taganito in the Philippines (Table 3).

Magmatic nickel-copper (-cobalt-PGE) deposits

This broad class comprises two principal deposit types related to mafic and ultramafic rocks emplaced in a variety of tectonic settings:

1. Magmatic sulfide deposits (nickel-copper-cobalt-PGE) (e.g. Figure 4A)

2. Magmatic PGE deposits in layered intrusions

Magmatic sulfide deposits account for about 40 per cent of global nickel production (Brown et al., 2019). Copper, cobalt and PGE, mainly palladium, are important co- or by-products. In some deposits gold, silver, chromium, sulfur, selenium, tellurium and lead are also recovered from the ore. These deposits are formed when mantle-derived magmas become saturated in sulfide and segregate into immiscible sulfide liquid, commonly following interaction with continental crustal rocks. Chalcophile elements such as nickel, copper, PGE and cobalt become relatively enriched in magmatic sulfide phases of these elements. For an economic deposit to form, sulfides precipitated from this liquid must be concentrated into a restricted physical space to constitute ore.

The dominant ore minerals in magmatic sulfide deposits are pyrrhotite, pentlandite and chalcopyrite, which generally constitute more than 10 per cent by volume of the host rock. Nickel grades are typically in the range 0.5–3.0% with attendant copper in the range 0.2–2.0% (Eckstrand & Hulbert, 2007). PGE contents vary widely from a few part per billion (ppb) up to, exceptionally, 10 ppm. Cobalt contents of iron-nickel-copper sulfide ores may reach up to several hundred parts per million (~500 to 1000 ppm) (Mudd et al., 2013). The size of the deposits ranges from a few hundred thousand tonnes up to a few tens of million tonnes of ore. Globally two nickel-copper districts are predominant, each containing more than 20 million tonnes of nickel metal, present in numerous deposits: Sudbury, Ontario, Canada and Noril'sk-Talnakh, Russia (Schulz et al., 2014).

The Sudbury mining district, which has been a major nickel producer for well over a century, is considered to be unique. Sulfide mineralisation is characterised by chalcopyrite, pyrrhotite and pentlandite with massive sulfides predominant at the base of the deposits, becoming more disseminated towards the top. Important by-products from the Sudbury deposits include PGE and cobalt. According to Roberts & Gunn (2014) cobalt occurs in minor quantities in pentlandite and pyrrhotite ranging from 0.4 to 1.3%. Naldrett (2004) reported an average Co grade of 0.038% in the Sudbury ores.

The Noril'sk-Talnakh deposits are examples of a group of nickel sulfide deposits associated with rift and continental flood basalt and associated dykes and sills, accounting for 215 million tonnes of ore reserves (C1 and C2 categories of the Russian Reserves and Resources Reporting System) grading 0.016% Co (Maslovskoye deposit) (Norilsk Nickel, 2016). Other similar examples include: the large deposits at Jinchuan in China (515 million tonnes of ore resources including reserves and past production grading 0.019% Co) (Slack et al., 2017); and in the Duluth Complex in USA (NI 43-101 compliant proven and probable ore reserves of 255 million tonnes grading 0.074% Co (Polymet Mining, 2018).

Another economically important class of magmatic sulfide deposits is associated with komatiitic lava flows, dykes and sills, mostly of Archaean and Proterozoic age. Under appropriate dynamic physical conditions the komatiitic ultramafic lavas and komatiitic basalts can host nickel mineralisation. Sills and feeder dykes related to komatiitic magmatism may also host nickel-copper-PGE ores. Many nickel deposits of this type are found in the Yilgarn Craton of Western Australia and include the world-class deposits at Kambalda and Mount Keith (Hoatson et al., 2006). Cobalt grades vary considerably in komatiite-associated deposits at Kambalda. Naldrett (2004) reported 0.21% Co at Kambalda, with a lower cobalt concentration of 0.014% in the ores at Mount Keith.

Most of the world's resources of PGE are hosted by layered mafic to ultramafic intrusions. The deposits in which they occur are mined primarily for their contents of platinum, palladium and rhodium, although ruthenium, iridium, osmium, gold, nickel, copper and chromium may also be recovered. Minor amounts of silver, cobalt, semimetals and metalloids, such as arsenic, antimony, bismuth and tellurium, may also be present in these ores. The deposits are formed essentially from the accumulation of crystals of metal oxides and sulfides during the cooling and crystallisation of the host magma. Two distinct styles of magmatic PGE mineralisation have been recognised in these intrusions: reef-type PGE deposits and copper-nickel-PGE contact-type deposits (Zientek, 2012; Zientek et al., 2017). The most important magmatic PGE deposits in layered intrusions are of the reef type and are located in the Bushveld Complex in South Africa, the Great Dyke in Zimbabwe and in the Stillwater Complex in the United States. Hitzman et al. (2017) reported Co grades of 0.03% in Bushveld ores. In the Great Dyke, sporadic iron hydroxide pseudomorphs after sulfides are veined by bluish grey manganese-cobalt-nickel-copper oxides and hydroxides which contain appreciable amounts of cobalt (7–18 wt%) (Oberthür et al., 2013).

Figure 4 **A**. Kevitsa magmatic sulfide nickel-copper-cobalt-PGE open-pit mine, mine depth 500 metres, northern Finland (Photo by Tomas Westermark/Boliden, (2016)). **B**. Overview of the volcanogenic massive sulfide (VMS)-style Kylylahti copper-cobalt-nickel-zinc underground mine, mine depth 700 metres, Outokumpu mining district, eastern Finland (Photo: Boliden (2015)).

Another important example of a magmatic sulfide deposit is Voisey's Bay in northern Labrador, Canada with JORC-compliant proven and probable cobalt ore reserves of 32.4 million tonnes grading 0.13% Co, equating to 42 000 tonnes of contained cobalt metal (Vale, 2017).

Other deposit types

Significant cobalt concentrations also occur in a wide range of other geological settings. Most deposits in these environments have produced relatively small amounts of cobalt, commonly as a by-product of mining copper, nickel, silver, lead or zinc.

Cobalt-copper-gold deposits in metasedimentary rocks

This diverse group includes deposits of disseminated to semimassive cobalt-bearing sulfarsenide and sulfide minerals associated with iron- and copper-bearing sulfides, and locally gold, in rift-related metasedimentary rocks chiefly of Proterozoic age (Slack et al., 2013). The primary commodities in these deposits are cobalt, copper and gold, with potential by-products including silver, bismuth, molybdenum, nickel, lead, REE, uranium, tungsten, yttrium and zinc. Their cobalt/copper ratios are generally higher than in other cobalt deposit types, with the exception of the stratiform copper deposits in the DRC. The best documented examples are those in the Blackbird district in Idaho, USA, Modum in Norway, Werner Lake in Ontario, Canada and Juomasuo in Finland (Slack et al., 2013). Given the diversity of mineralisation present within deposits of this class, it is difficult to develop a single genetic model for their origin. Various authors have invoked a range of processes, including syngenetic, diagenetic, post-tectonic and synmetamorphic mineralisation.

Polymetallic and other cobalt-rich vein deposits

Cobalt-rich vein deposits, comprising mostly multistage silver and cobalt mineralisation, were mined in the past in several countries including the Erzgebirge region of the Czech Republic and Germany, the Kongsberg district of Norway and the Cobalt district of Ontario, Canada (Slack et al., 2017). In some of these districts by-product copper, lead, zinc, gold, uranium and barytes have also been extracted.

The most important district of this type and the only one where cobalt is currently produced as a primary commodity is Bou Azzer in the Central Anti-Atlas Mountains of southern Morocco (Bouabdellah et al., 2016). More than 100 cobalt-nickel-iron deposits are known in this district associated with a Neoproterozoic ophiolite complex. Twelve of these deposits have been, or are currently being, mined down to a maximum depth of 300 metres. The average annual production in the district is 100 000 tonnes of ore grading about 1% Co, 1% Ni, 3–42 ppm Ag and 3–4 ppm Au. Bouabdellah et al. (2016) have recognised three hydrothermal stages of mineralisation dominated by arsenide and sulfarsenide mineral phases including skutterudite, safflorite, loellingite, nickeline and rammelsbergite, with accessory copper sulfides, molybdenite, gold and electrum.

The deposits in the Cobalt area of northern Ontario, Canada, were major sources of silver in the early part of the 20th century. Approximately 445 million troy ounces (about 12.6 tonnes) of silver, together with over 20 000 tonnes of cobalt, were produced from more than 40 mines from 1903 onwards (Marshall & Watkinson, 2000). Native silver mineralisation occurs in these deposits in association with cobalt arsenides, sulfarsenides and sulfosalts in near-vertical carbonate veins cutting Archaean greenstones, Proterozoic metasedimentary rocks and the Palaeoproterozoic Nipissing diabase. Although the processes responsible for the formation of these deposits remain unclear, fluid inclusion studies suggest that the Nipissing diabase supplied heat and fluids with silver transported as chloride complexes in highly saline brine (Marshall & Watkinson, 2000).

Iron-oxide-copper-gold deposits

The iron-oxide-copper-gold (IOCG) class of deposits is an ill-defined grouping with no consensus on the processes responsible for their formation. The key empirical features of IOCG deposits include the presence of economic copper grades with or without associated gold, hydrothermal vein, breccia and/or replacement ore styles, abundant magnetite and/or haematite and the lack of any clear spatial association with igneous intrusions (Williams et al., 2005). They are commonly associated with pervasive sodic or sodic-calcic alteration. The ores may be enriched in minor elements like cobalt, silver, uranium, REE, phosphorus, molybdenum, barium and fluorine. IOCG deposits tend to be large multi-commodity deposits amenable to large-scale mining operations. The largest deposit, and perhaps the most well known, is Olympic Dam in South Australia. It is a major producer of copper, uranium, gold and silver, but cobalt is not currently recovered from these ores. Total resources and past production at Olympic Dam have been estimated at 605 million tonnes grading 0.02% Co (Williams & Pollard, 2001). This equates to an endowment of 121 000 tonnes of cobalt metal.

Volcanogenic massive sulfide deposits

Volcanogenic massive sulfide (VMS) deposits are major global sources of copper, lead, zinc, gold and silver in deposits varying in age from Archaean to Holocene. In association with ultramafic or mafic volcanic rocks, VMS deposits may contain high cobalt concentrations e.g. deposits at Windy Craggy in north-western British Columbia, Canada, at Deerni in Qinghai Province, China and several in Russia (Slack et al., 2017).

The VMS-style Kylylahti copper-cobalt-nickel-zinc deposit (Figure 4B) in the Outukumpu district of south-eastern Finland has mineral resources of 6.8 million tonnes grading 0.11% Co with additional mineral reserves of 1.3 million tonnes grading 0.17% Co (PERC Reporting Standard), but the mine is coming to the end of its life (Boliden, 2018). At Kylylahti 278 tonnes of cobalt were produced by Boliden in 2018 as a by-product of copper (Boliden, 2018).

Skarn and replacement deposits

Skarn and replacement deposits occur in carbonate rocks spatially associated with intrusive igneous bodies. They may contain a wide variety of metals, including cobalt at a few localities. Large cobaltiferous skarn deposits are known in Pennsylvania, USA (0.025% Co in the Cornwall deposit) and at Magnitogorsk (0.018% Co) and Goroblagodat (0.022% Co) in Russia (Slack et al., 2017). Cobalt concentrations close to 0.1% have been reported in the Mount Elliott copper-gold Proterozoic skarns in the Cloncurry district of Queensland, Australia (Wang & Williams, 2001). Cobalt, in the form of carrolite, is also locally common in the Ruby Creek copper skarn deposit in Alaska, USA (Bernstein & Cox, 1986).

Black shale-hosted nickel-copper-zinc-cobalt deposits

Several metals, including copper, nickel, molybdenum, vanadium, uranium and cobalt, may be enriched in black, organic-rich shales. Metal enrichment may be due chiefly to primary sedimentological processes, although diagenetic and epigenetic processes commonly play a significant role in increasing metal concentrations.

The most important black-shale deposit from which cobalt has been extracted is at Talvivaara, also referred to as Sotkamo, in central Finland (Loukola-Ruskeeniemi & Lahtinen, 2013). This is a very large low grade deposit with resources estimated at 2053 million tonnes grading 0.02% Co, equivalent to a total endowment of 411 000 tonnes of cobalt metal (Slack et al., 2017). In addition to cobalt, nickel, zinc and copper are also extracted from these ores (Terrafame, 2018). The company also plans to produce uranium at this location.

Mississippi Valley-type zinc-lead deposits

Mississippi Valley-type (MVT) deposits are important global sources of zinc and lead. They comprise stratabound sulfide ores hosted by carbonate rocks, mostly Phanerozoic in age. In a few cases elevated cobalt contents are present in MVT deposits. Slack et al. (2017) reported minor cobalt production from two lead-zinc mines in Missouri, USA (Table 3). Parra Avila (2010) documented anomalous average grades for the Higdon deposit in south-east Missouri (0.17% Ni, 0.14% Co) occurring in siegenite, bravoite, gersdorffite and marcasite-pyrite.

Orogenic gold deposits

Cobalt enrichment is not widely documented in orogenic gold deposits. However, a notable example has been reported at Rajapalot in the Karelia tectonic province in Finnish Lapland (AMC Consultants, 2018). The mineralisation is located within a Palaeoproterozoic supracrustal sequence overlying Archaean basement. Two distinct styles of gold mineralisation have been reported: a variably sulfidic magnesian iron formation associated with minor cobaltian pentlandite and cobaltite and quartz veining; and a gold-cobalt disseminated type associated with potassic-iron alteration in a wide range of fabrics. The formation of these two types of mineralisation is not well understood, nor is the relationship between them.

Seafloor cobalt resources

Ferromanganese nodules

On sediment-starved deep ocean floors, particularly at water depths of 4.5–6 kilometres, nodules rich in iron and manganese can form around small fragments of debris and organic material (Slack et al., 2017). These nodules are derived from the precipitation of iron and manganese oxide colloids over millions of years. Under favourable environmental conditions, they scavenge dissolved metals from two sources, seawater (hydrogenetic) and pore fluids (diagenetic). The nodules (Figure 5), typically 1–5 centimetres in size, are strongly enriched relative to the Earth's crust in nickel, copper, cobalt and a range of other metals (Hein et al., 2013). Their occurrence in proximity to mid-ocean rises suggests a volcanogenic source for mineral enrichment. They can occur as densely packed sheets and cover areas of hundreds of square kilometres. The largest known ferromanganese nodule fields are located in the eastern equatorial Pacific Ocean between the Clarion and Clipperton fracture zones (CCZ), in the Cook Islands Exclusive Economic Zone (EEZ), in the Penrhyn-Samoa Basin, the Peru Basin and in the Pioneer area of the central Indian Ocean (Hein et al., 2013). Cobalt grades in these nodules seldom exceed 2000 ppm, but, given the high nodule densities and the vast extent of the nodule fields, the resource potential is very large. Hein et al. (2013) reported that the CCZ alone contains 21 billion tonnes of nodules with a cobalt content of 44 million tonnes, which is 5.5 times larger than land-based cobalt reserves.

Ferromanganese crusts

Ferromanganese crusts (Figure 5) form through precipitation from seawater onto most indurated surfaces in the marine environment. They are found at water depths of 400 to 7000 metres on the flanks and summits of seamounts where the rocks are free of sediment (Hein & Koschinsky, 2014). The thickest and most metal-rich crusts form at water depths of about 800 to 2500 metres (Hein et al., 2009; Hein et al., 2000). Crust thickness varies greatly on both regional and local scales: they are commonly a few centimetres thick, but locally may reach 25 centimetres. Given that the growth rate of ferromanganese crusts is very slow, in the range of 1–10 millimetres per million years, the thickest crusts and thus the largest resources are found on the oldest seamounts. The north-west Pacific Ocean, which has the oldest known oceanic lithosphere and the greatest number of large seamounts, has the greatest abundance of ferromanganese crusts. The Prime Crust Zone (PCZ) in the central and western equatorial Pacific is currently of greatest economic interest (Hein et al., 2013). The potential for crusts in the Atlantic Ocean has been less thoroughly investigated but crusts are known to be widespread (Lusty et al., 2018). The cobalt content of ferromanganese crusts can be up to 2%, but generally averages between 0.3 and 0.7% (Hein et al., 2013). Other metals of potential economic importance in crusts include nickel, tellurium, rare earth elements (REE) and PGE.

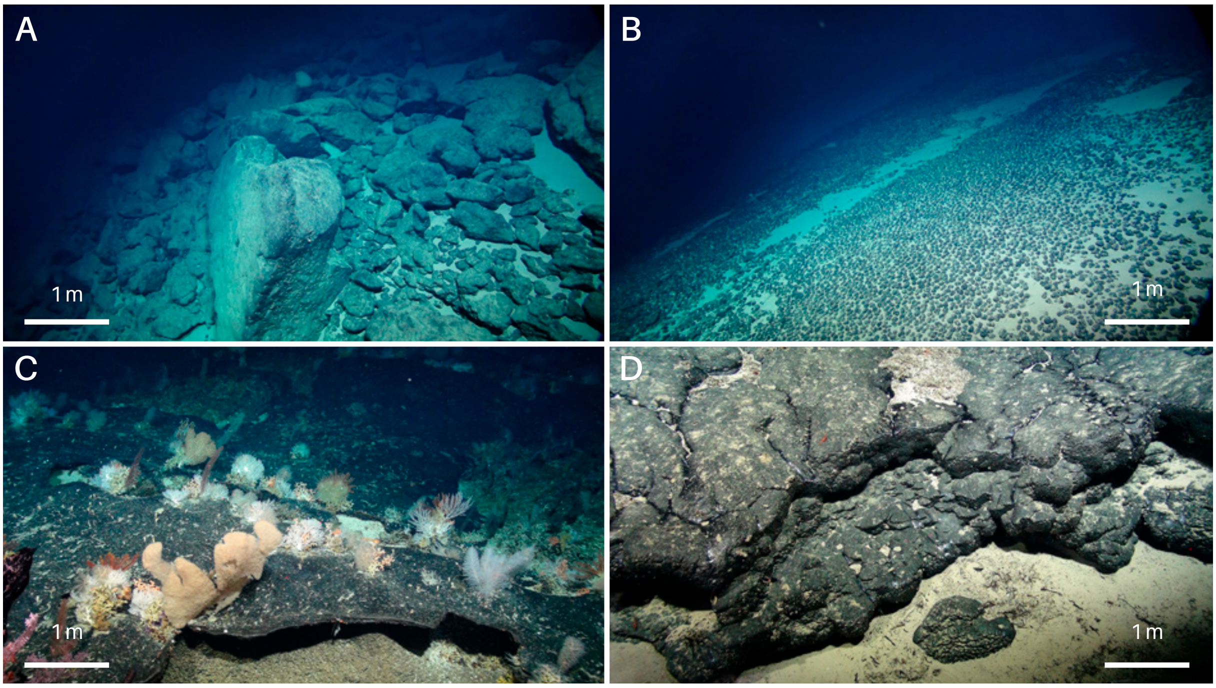


Figure 5 Ferromanganese crusts and nodules on Tropic Seamount (Atlantic Ocean). **A**. Encrusted debris flow cobbles on the steep flanks of the seamount (depth 1450 metres). **B**. A nodule field in a sediment-rich area on the flank of the seamount (depth 3640 metres). **C**. Ferromanganese crust pavement covered by biological debris on a gentle slope on the seamount flank (depth 1600 metres). **D**. Massive ferromanganese crust partially covered in sediment (depth 3772 metres) (Lusty et al., 2018).

Advanced exploration projects

The forecast continued growth in demand for cobalt requires a pipeline of new projects. Numerous cobalt exploration projects are underway worldwide, some focussing on conventional deposit types, such as sediment-hosted stratiform and magmatic sulfide deposits, and others on 'unconventional' targets. Selected examples of these projects are summarised below.

Africa

Measured and indicated resources of the Kamoto Copper Company (KCC) mining assets in the DRC are 275.6 million tonnes grading 0.54% Co (NI 43-101 Reporting Standard) (Katanga Mining Limited, 2019). The project has been delayed by operational, legal and financial issues since 2016, but remains one of the world's largest cobalt exploration projects (Ali et al., 2018).

The Australian exploration company Jervois Mining Limited is evaluating cobalt occurrences in Uganda close to the DRC border. They share the same underlying geology and are on trend with a number of major cobalt-producing mines in the DRC. The Kilembe and Bujagali properties are key areas ranked as top cobalt targets by the Geological Survey of Finland (GTK), with ore assays of 0.25% Co at Kilembe. Initial rock grab samples from Bujagali contain up to 1.24% Co (Jervois Mining, 2019a).

The Opuwo Cobalt Project in north-western Namibia, owned by Celsius Resources Limited, is a large cobalt resource with favourable mineralogy and low levels of deleterious elements, especially arsenic, cadmium and uranium (Celsius Resources, 2018). Resource drilling completed in late 2017 gave a JORC-compliant indicated and inferred resource of 112.4 million tonnes grading 0.11% Co at a cut-off grade of 0.06% Co.

North America

Fortune Minerals Limited is planning to develop a mine to exploit the IOCG-type NICO cobalt-gold-bismuth deposit in the Northwest Territories of Canada. Proven and probable minerals reserves total 33 million tonnes, containing about 37 200 tonnes of cobalt in open pit and 600 tonnes underground (NI 43-101 Reporting Standard) (Fortune Minerals Limited, 2014). Test mining and pilot plant validation have been successfully completed on this deposit (Fortune Minerals Limited, 2019).

The Dumont nickel-cobalt magmatic sulfide deposit located in the Abitibi region of southern Quebec, Canada may represent the 2nd largest nickel reserve in the world and the 9th largest cobalt reserve (2nd largest undeveloped cobalt reserve) (RNC Minerals, 2019). In May 2019 NI 43-101-compliant measured and indicated resources of cobalt metal were 180 000 tonnes, with proven and probable reserves of 110 223 tonnes cobalt (RNC Minerals, 2019).

Battery Mineral Resources is exploring widely in the Ontario Cobalt Belt beyond the historic silver district, north of the Sudbury Basin. Assay results of samples from outcrops have yielded high cobalt values ranging from 1.5% to 21% (Battery Mineral Resources, 2018). NI 43-101-compliant indicated mineral resources at the McAra project amount to 72 000 tonnes grading 1.27% Co (Battery Mineral Resources, 2018).

The Idaho Cobalt belt project is centred on the abandoned Blackbird mine complex in the cobalt-copper district in the Salmon River Mountains of east-central Idaho, USA (Bookstrom et al., 2016). Measured and indicated mineral resources are estimated at 3.87 million tonnes grading 0.59% Co, making it the largest NI 43-101 compliant cobalt resource in the United States (Jervois Mining, 2019b).

Cobalt27, a leading electric metals investment company, owns approximately 2905 tonnes of physical cobalt, directly providing cobalt for EVs and the battery energy storage market (Cobalt27, 2018). The acquisition of the US$300 million cobalt stream at Vale's Voisey's Bay mine, scheduled to begin in 2021, includes ore remaining in the open pit and from the full Voisey's Bay Mine Expansion (VBME) underground operations. Cobalt27 will receive 32.6 per cent of cobalt production from the mine, equating to approximately 861 tonnes of cobalt per year (Cobalt27, 2018).

Australia

The Thackaringa Cobalt project, owned by Cobalt Blue Holdings Limited, is located near Broken Hill, in New South Wales. JORC-compliant indicated mineral resources comprise 72 million tonnes at 852 ppm Co for 61 500 tonnes contained cobalt (Cobalt Blue, 2019).

The Sunrise project in New South Wales is owned by Clean TeQ Holdings and China's Pengxin International Mining (16.5 per cent stake). This world-class nickel, scandium and cobalt project is one of the highest grade and largest nickel-cobalt deposits outside Africa. Clean TeQ reported a JORC-compliant measured resource of 39.9 million tonnes grading 0.15% Co using a 0.06% cut-off with proven and probable reserves of 147.4 million tonnes grading 0.09% Co (Clean Teq, 2018).

The NiWest Nickel-Cobalt Project is located in the Western Australian nickel belt near Glencore's Murrin Murrin nickel-cobalt operation. It is regarded as one of the largest and highest quality undeveloped nickel-cobalt laterite resources in Australia with JORC-compliant measured and indicated mineral resources of 85 million tonnes grading 1.03% Ni and 0.07% Co at a 0.8% Ni cut-off grade (GME Resources, 2018).

South America

In Chile, cobalt resources are limited to copper-gold-cobalt manto and vein type deposits in the Atacama region. Exploration campaigns in 1983 by Geoexploraciones in the San Juan district, near the city of Huasco, indicated cobalt concentrations in samples from primary ores and outcrops of 0.001–1.95%. Remaining in-situ stockpile mineral resources in this district amount to 67 260 tonnes with cobalt grades ranging from 0.05–1%. The historical cobalt mines El Buitre and Minillas in the Tambillos district, south of La Serena, are both manto-type deposits. The El Buitre mine was largely exploited for cobalt in 1975 at three different levels with ore bodies and remaining waste from past mining having estimated contents of about 1% and 0.46% Co, respectively. The Minillas mine is presently in preparation for exploitation (Townley et al., 2017).

Europe

There is considerable interest in the cobalt resource potential of the EU. There are three operating mines in Finland that currently produce by-product cobalt. In addition, there are a number of ongoing exploration projects where cobalt is a target commodity.

Boreal Metals Corp. owns several projects in former mining districts in Sweden and Norway (Boreal Metals, 2019). For example, the Guldgruvan Cobalt project near the town of Los, Gävleborg County, Sweden, contains the historic Los Cobalt Mines which were important sources of cobalt, copper and nickel in the seventeenth and eighteenth centuries. In this area cobalt-bearing copper and subordinate nickel-zinc-gold-silver mineralisation occurs in sulfide disseminations, vein infill and shear zones within Proterozoic mafic and felsic metavolcanic rocks at Cobaltgruvan (Boreal Metals, 2019).

Carnaby Resources, formerly Berkut Minerals Ltd, is exploring at the Skuterud Project in southern Norway (Carnaby Resources, 2019). This project is focussing on a major historical producing region, which includes the famous Skuterud cobalt mine that supplied much of the world's cobalt during the 18th and 19th centuries. The former workings extend over a strike length of at least nine kilometres hosted by a sulfide-rich schist zone of metasedimentary origin.

FinnCobalt, a private Finnish company, owns the former cobalt-nickel-copper mine at Hautalampi, located close to the historic Outokumpu copper mine in eastern Finland. A feasibility study was completed in 2008 which reported a NI-43-101-compliant reserve of 2.2 million tonnes grading 0.38% Ni, 0.10% Co and 0.32% Cu (FinnCobalt, 2019). Mining and environmental permits have been approved at Hautalampi and metallurgical testwork is ongoing.

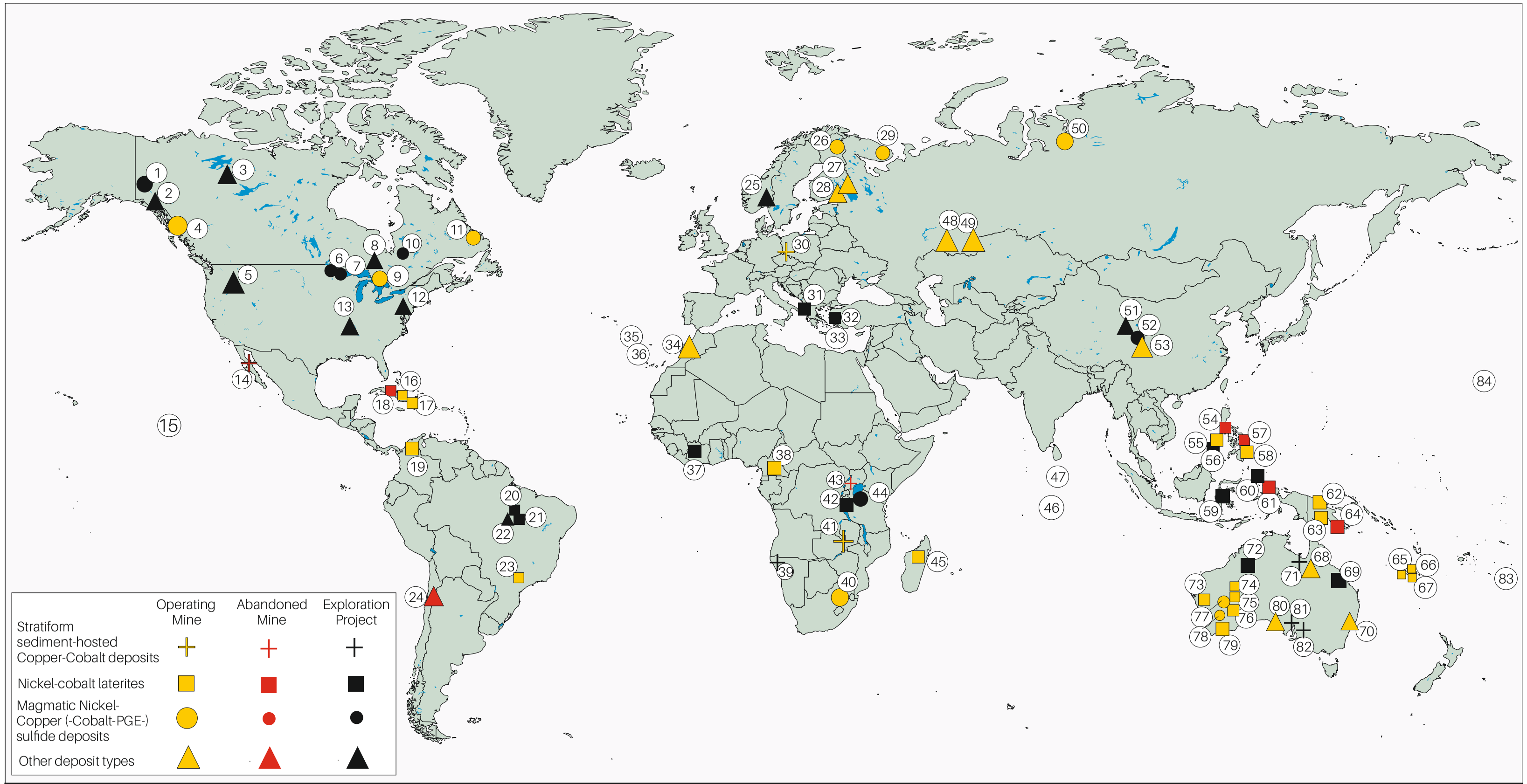
The magmatic copper-nickel-PGE Sakatti deposit in northern Finland was discovered by Anglo American in 2009. JORC-compliant measured and indicated mineral resources total 3.5 million tonnes grading 0.11% Co (Anglo American, 2018).

The Rompas Rajapalot gold-cobalt project is located a few kilometres south of the Arctic Circle in the municipality of Ylitornio in Finnish Lapland. Here Mawson Resources is exploring an orogenic style gold deposit that contains significant cobalt resources (AMC Consultants, 2018). At the end of 2018 Mawson Resources Limited reported an NI 43-101 inferred mineral resource at Rajapalot of 4.3 million tonnes grading 2.3 g/t Au and 430 ppm Co (AMC Consultants, 2018).

There is also considered to be potential for cobalt resources associated with the sediment-hosted stratiform copper-silver deposits in the Zechstein Basin in Poland. However, there is no information in the public domain concerning the abundance and distribution of cobalt in these deposits.

Other exploration projects

Although cobalt exploration is ongoing in several countries there is no certainty that this will result in new mine production of cobalt. Current notable cobalt exploration projects include: Kipoi stratiform sediment-hosted copper project, DRC (JORC-compliant measured and indicated mineral resources of 57.4 million tonnes grading 0.07% Co) (Tiger Resources, 2017); Weda Bay nickel-cobalt laterite deposit, Indonesia, owned by Eramet and the Tsingshan group, with estimated total mineral resource of 117 million tonnes grading 0.12% Co (Mining Journal, 1999); Ta Khoa magmatic nickel sulfide deposit, Vietnam (Blackstone Minerals, 2019); Duhamel nickel-copper-cobalt property, Canada (International Montoro Resources, 2018); Gogota cobalt-nickel-scandium laterite deposit, Guinea (total resources in limonite of 38 million tonnes grading 0.07% Co) (SRG Mining, 2018); Carmenes porphyry cobalt-copper deposit, Spain (Riedel Resources, 2018); Jouhineva polymetallic (cobalt-copper-gold) vein deposit, Finland (European Cobalt, 2017); cobalt-copper-nickel-containing waste dumps of the historical Kolba deposit, and Dobsina cobalt-rich vein deposit in Slovakia (European Cobalt, 2017).



1 Wellgreen
2 Windy Craggy
3 NICO
4 Turnagain
5 Blackbird district
6 Nokomis
7 Northmet
8 Cobalt-Gowganda district
9 Sudbury
10 Dumont
11 Voisey's Bay
12 Cornwall/Morgantown
13 Mine La Motte/Fredericktown
14 Boleo
15 Clarion Clipperton Zone
16 Punta Gorda
17 Nicaro
18 Moa
19 Cerro Matosa
20 Jacaré
21 Vermelho
22 Itapitanga
23 Niquelandia
24 Candelaria
25 Modum district
26 Kevitsa
27 Sotkamo
28 Kylylahti
29 Pechenga
30 European Kupferschiefer
31 Bitincke
32 Caldag
33 Nameless
34 Bou Azzer
35 Madeira-Tore Rise
36 Unicorn
37 Tiuba-Biankouma
38 Nkamouna
39 Opuwo
40 Nkomati
41 CACB
42 Musongati
43 Tiuba-Biankouma
44 Kabanga
45 Ambatovy
46 Pioneer
47 Afanasiy-Nikitin
48 Magnitogorsk
49 Gaiskoye
50 Norilsk-Talnakh
51 Deerni
52 Jinchuan
53 Lala
54 Mindoro
55 Ipilan
56 Coral Bay
57 Taganito
58 Nonoc
59 La Sampala
60 Weda Bay
61 Gag Island
62 Ramu
63 Wowo Gap
64 Mambare
65 Thio
66 Nakety
67 Goro
68 Ernest Henry
69 Marlborough Cobalt
70 Mount Elliot
71 Mount Isa
72 Wingellina
73 Weld Range
74 Cawse
75 Murrin Murrin
76 Kalgoorlie
77 Kambalda Dome
78 Mt Keith
79 Ravensthorpe
80 Olympic Dam
81 Emmie Bluff/Windabout
82 Thackaringa Cobalt
83 Cook Islands EEZ
84 Pacific Prime Crust Zone

Figure 6 Selected cobalt deposits worldwide including operating and abandoned mines and advanced exploration projects. The cobalt endowment of each deposit shown exceeds 0.05 million tonnes of cobalt metal, with the exception of some exploration projects in Europe (see Table 3 for details). Other deposit types include: black shale-hosted Ni-Cu-Zn-Co; Fe-Cu-Co skarn and replacement deposits; IOCG; metasedimentary rock-hosted Co-Cu-Au; MVT sulfide deposits; cobalt-rich vein deposits; VMS deposits. Note: the approximate location of seafloor deposits is shown by a number only, without an accompanying symbol.

Table 3 Location, current status, cobalt grade, contained cobalt metal and deposit tonnage of selected cobalt deposits worldwide.

	Operating mine	Abandoned mine	Exploration project	Co grade (%)	Co metal content (million tonnes)	Deposit tonnage (million tonnes)	Reference
Stratiform sediment-hosted Cu-Co deposits							
Boleo, Mexico	X			0.05	0.23	424.5	Slack et al. (2017)
CACB-DRC Tenke Fungurume deposits	X			0.25	1.69	674.0	Slack et al. (2017)
CACB-DRC Tilwezembe	X			0.64	0.15	23.4	Slack et al. (2017)
CACB-DRC Kisanfu			X	1.08	1.17	108.0	Slack et al. (2017)
CACB-DRC Kamoto-KOV	X			0.39	1.61	416.0	Slack et al. (2017)
CACB-Zambia Baluba-Muliashi-Luanshya	X			0.03	0.11	339.0	Slack et al. (2017)
CACB-Zambia Chambishi Southeast	X			0.07	0.12	178.0	Slack et al. (2017)
Opuwo Cobalt Project, Namibia			X	0.11	0.12	112.4	Celsius Resources (2018)
Thackaringa Cobalt, Broken Hill, Australia			X	0.14	0.10	72.0	Cobalt Blue (2018)
Emmie Bluff, Australia			X	0.10	0.03	25.0	Slack et al. (2017)
Windabout, Australia			X	0.05	0.01	17.7	Gindalbie Metals (2018)
Mount Isa, Australia	X			0.05	0.09	182.0	Slack et al. (2017)
Ni-Co laterites							
Kalgoorlie Nickel Project, Australia	X			0.05	0.39	773.0	Ardea Resources (2019)
Murrin Murrin, Australia	X			0.08	0.18	231.0	Glencore (2018a)
Marlborough Cobalt, Australia			X	0.06	0.13	210.0	Berger et al. (2011)
Ravensthorpe, Australia	X			0.03	0.10	386.0	Berger et al. (2011)
Weld Range, Australia	X			0.06	0.20	330.0	Slack et al. (2017)
Wingellina, Australia			X	0.07	0.27	384.2	Metals X Limited (2016)
NiWest Project, Australia			X	0.07	0.06	85.0	GME Resources (2018)
Sunrise Project, Australia			X	0.09	0.17	187.3	Clean Teq (2018)
Cawse, Australia	X			0.04	0.09	217.0	Berger et al. (2011)
Goro deposit, New Caledonia	X			0.11	0.36	323.0	Berger et al. (2011)
Nakety, New Caledonia	X			0.12	0.27	229.0	Berger et al. (2011)
Thio, New Caledonia	X			0.10	0.21	208.0	Berger et al. (2011)
Mambare, Papua New Guinea		X		0.09	0.15	162.5	Regency Mines (2019)
Ramu, Papua New Guinea	X			0.10	0.14	143.2	Berger et al. (2011)
Wowo Gap, Papua New Guinea	X			0.06	0.11	190.0	Berger et al. (2011)
Nkamouna and Mada, Cameroon	X			0.22	0.86	391.5	Slack et al. (2017)
Moa, Cuba	X			0.13	0.25	191.0	Sherritt International Corp (2019)
Punta Gorda, Cuba		X		0.11	0.34	310.0	Slack et al. (2017)
Nicaro, Cuba	X			0.10	0.20	200.0	Slack et al. (2017)
Caldag, Turkey			X	0.05	0.02	37.9	Slack et al. (2017)
Musongati, Burundi			X	0.08	0.15	185.0	Berger et al. (2011)
Ambatovy, Madagascar	X			0.09	0.15	164.4	Berger et al. (2011)
Coral Bay (Rio Tuba), Philippines	X			0.12	0.07	57.7	Slack et al. (2017)
Taganito, Philippines	X			0.12	0.14	123.0	Slack et al. (2017)
Nonoc, Philippines		X		0.11	0.16	144.7	Slack et al. (2017)
Ipilan, Philippines			X	0.10	0.08	77.0	Slack et al. (2017)
Mindoro, Philippines		X		0.06	0.19	315.0	Slack et al. (2017)
Jacare, Brazil			X	0.13	0.64	495.0	Berger et al. (2011)
Niquelandia, Brazil	X			0.06	0.03	56.3	Berger et al. (2011)

Vermelho, Brazil			X	0.06	0.10	170.6	Horizonte Minerals (2018)
Gag Island, Indonesia		X		0.08	0.19	240.0	Berger et al. (2011)
Halmahera/Weda Bay, Indonesia			X	0.09	0.25	277.0	Berger et al. (2011)
La Sampala, Indonesia			X	0.08	0.13	162.0	Berger et al. (2011)
Tiuba-Biankouma, Ivory Coast			X	0.11	0.32	293.0	Berger et al. (2011)
Magmatic Ni-Cu (-Co-PGE) sulfide deposits							
Kambalda Dome, Australia	X			0.21	0.14	67.0	Naldrett (2004)
Mt. Keith, Australia	X			0.01	0.07	478.0	Naldrett (2004)
Sudbury, Canada	X			0.04	1.01	2648.0	Glencore (2018b)
Dumont, Canada			X	0.01	0.23	2134.2	Slack et al. (2017)
Turnagain, Canada			X	0.01	0.24	1841.8	Giga Metals (2019)
Wellgreen (Nickel Shäw), Canada			X	0.02	0.09	431.5	Marek et al. (2018)
Voisey's Bay, Canada	X			0.09	0.12	137.0	Naldrett (2004)
Jinchuan, China			X	0.02	0.10	515.0	Naldrett (2004)
Norilsk-Talnakh, Russia	X			0.06	0.80	1309.0	Naldrett (2004)
Pechenga, Russia	X			0.05	0.15	339.0	Slack et al. (2017)
Nokomis mines (Twin Metals), USA			X	0.01	0.26	2614.2	Duluth Metals Corp (2014)
Northmet, USA			X	0.01	0.12	1158.2	Polymet Mining (2018)
Kevitsa, Finland	X			0.01	0.03	333.2	Boliden (2018, 2019)
Sakatti, Finland			X	0.11	0.05	44.40	Anglo American (2017)
Seafloor Fe-Mn(-Ni-Cu-Co-Mo) nodules							
Clarion-Clipperton Zone, Pacific Ocean			X	0.21	44.0	21100.0	Slack et al. (2017)
Cook Islands EEZ, Pacific Ocean			X	0.41	21.0	5122.0	Hein et al. (2013)
Pioneer, Indian Ocean			X	0.10	0.700	700.0	Slack et al. (2017)
Seafloor Fe-Mn(-Co-Mo-REE) crusts							
Pacific prime crust zone, Pacific Ocean			X	0.66	50.019	7533.0	Hein et al. (2013)
Nameless, Atlantic Ocean			X	0.34	0.241	71.0	Slack et al. (2017)
Unicorn, Atlantic Ocean			X	0.35	0.455	130.0	Slack et al. (2017)
Maderia-Tore Rise (MTR), Atlantic Ocean			X	0.35	3.850	1100.0	Slack et al. (2017)
Afanasiy-Nikitin seamount, Indian Ocean			X	0.58	1.044	180.0	Slack et al. (2017)
Other deposit types*							
Blackbird district, Idaho Cobalt Belt, USA[4]			X	0.59	0.07	11.3	Jervois Mining (2019a)
Talvivaara (Sotkamo), Finland[1]	X			0.02	0.411	2053.0	Slack et al. (2017)
Cornwall and the Morgantown, USA[2]	X			0.03	0.025	100.0	Slack et al. (2017)
Magnitogorsk, Russia[2]	X			0.02	0.090	500.0	Slack et al. (2017)
Olympic Dam, Australia[2]	X			0.02	0.121	605.0	Slack et al. (2017)
Ernest Henry, Australia[3]	X			0.05	0.083	166.0	Slack et al. (2017)
Lala (Lalachang), China[3]	X			0.02	0.044	200.0	Slack et al. (2017)
NICO, Canada[4]			X	0.11	0.036	33.0	Fortune Minerals Limited (2014)
Bou Azzer, Morocco[5]	X			1.00	0.057	5.7	Bouabdellah et al. (2016)
Kylylahti, Outokumpu district, Finland[6]	X			0.11	0.015	13.0	Boliden (2018)
Windy Craggy, Canada[6]			X	0.66	1.960	297.0	Hitzman et al. (2017)
Deerni, Qinghai Province, China[6]	X			0.08	0.043	54.0	Slack et al. (2017)
McAra, Ontario Cobalt Belt (OCB), Canada[6]			X	1.04	0.749	72.0	Battery Mineral Resources (2018)
Gaiskoye (Gai and Gai East), Russia[6]	X			0.02	0.060	300.0	Slack et al. (2017)

[1]Black shale-hosted Ni-Cu-Zn-Co; [2]Fe-Cu-Co skarn and replacement; [3]IOCG; [4]Metasedimentary-rock-hosted Co-Cu-Au; [5]Cobalt-rich vein; [6]VMS

World resources and reserves

According to Slack et al. (2017), the total terrestrial cobalt resource (including past production, where available) is 25.5 million tonnes of contained cobalt, which is comparable to the terrestrial cobalt resource of 26.1 million tonnes of contained cobalt calculated by Mudd et al. (2013). Cobalt deposits vary greatly in size, with most containing between 5000 and 500 000 tonnes of cobalt (Figure 7). The largest deposits, but with generally low cobalt grades, belong to the magmatic nickel-copper (-cobalt-PGE) type. Stratiform sediment-hosted copper-cobalt deposits vary considerably in both grade, from 0.03 to 1.08% Co, and size. The largest deposits are at Tenke Fungurume in the DRC, with an aggregate tonnage of 674 million tonnes of ore. Lateritic nickel-cobalt deposits appear to have a more restricted range of size and grade (0.03–0.22% Co). Individual examples of other deposit types, such as the cobalt-rich vein deposit at Bou Azzer in Morocco and the metasedimentary-hosted deposits in the Blackbird district of Idaho, are characterised by high cobalt grades, up to 1.0%, but low ore tonnages.

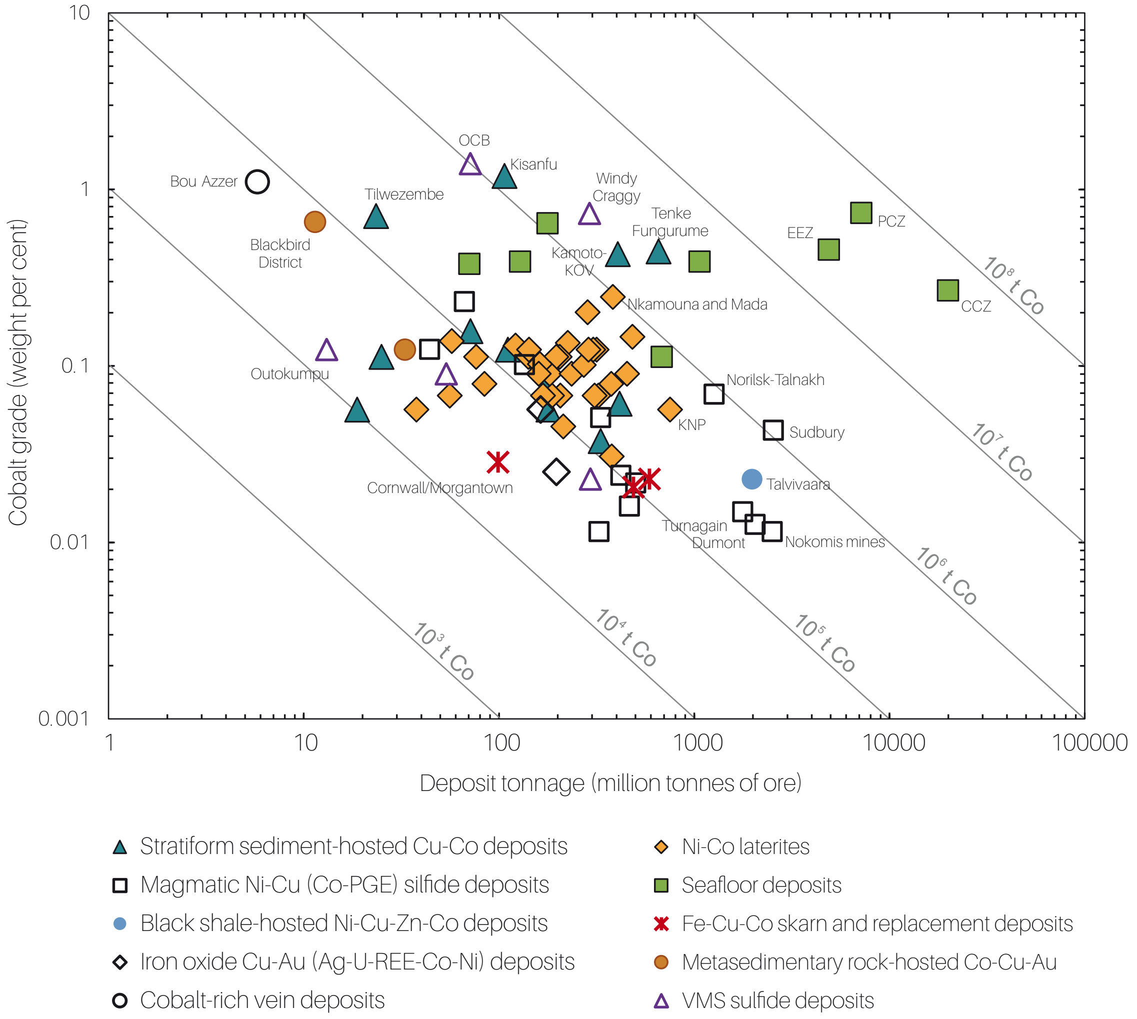


Figure 7 Grade-tonnage plot for 79 cobalt deposits worldwide. Deposit tonnage includes past production and resources and reserves (where known). Abbreviations: KNP-Kalgoorlie nickel project, OCB-Ontario Cobalt Belt, EEZ-Cook Islands Exclusive Economic Zone, PCZ-Pacific Prime Crust Zone, CCZ-Clarion-Clipperton Zone. Diagonal lines indicate contained cobalt metal. (Data sources: Slack et al. (2017), company annual reports, company investor presentations, company websites).

Seafloor deposits are estimated to contain the most cobalt metal. Seafloor ferromanganese (Fe-Mn) crusts have cobalt contents up to about two per cent and typical concentrations for large areas of the global ocean range from 0.30 to 0.67% (Hein et al., 2000; Hein et al., 2013). Iron-manganese crusts from the Prime Crust Zone in the Pacific Ocean have a mean cobalt concentration of 0.66% and are estimated to contain 50 million tonnes of cobalt metal (Hein et al., 2013). Another major concentration of cobalt is in seafloor polymetallic (Fe-Mn-Ni-Cu-Co-Mo) nodules, with the most extensive deposits having typical cobalt grades ranging between 0.05 and 0.21%. The most significant deposits have been discovered in the Clarion-Clipperton Zone in the eastern Pacific Ocean and are estimated to contain 44 million tonnes of cobalt metal (Slack et al., 2017; Hein et al., 2013).

Of the recoverable terrestrial cobalt resources identified by Mudd et al. (2013) almost 42 per cent occur in nickel-cobalt laterites, with 39 per cent in stratiform sediment-hosted deposits. Almost 11 per cent occur in IOCG deposits and seven per cent in magmatic sulfide deposits. It should be noted that the data used to allocate resources to each deposit type are of variable quality and will also change over time (Mudd et al., 2013) (Figure 8).

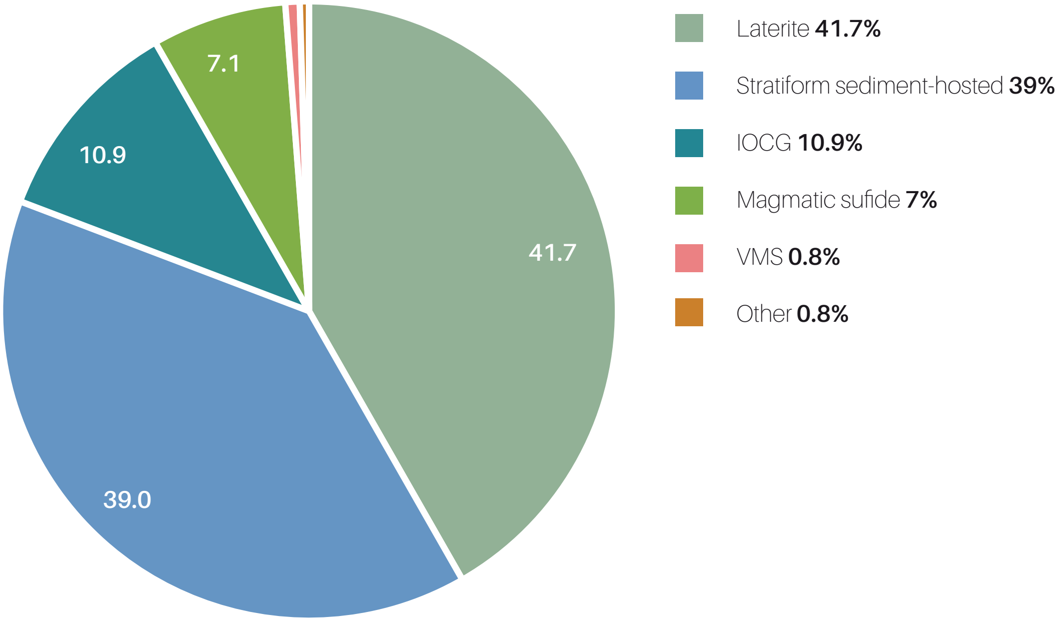


Figure 8 Recoverable terrestrial cobalt resources by deposit type. Total resources amount to 15.4 million tonnes. (calculated from data in Mudd et al. (2013)).

The largest share of global terrestrial resources is located in the Central African Copper Belt (CACB) in the DRC and Zambia with about 15 million tonnes of cobalt (Hitzman et al., 2017). In the CACB, those deposits with economic (by-product) cobalt are located mostly in the Congo Copperbelt (CCB) and the western part of the Zambian Copperbelt (ZCB). The Tilwezembe anticline in the CCB contains the most cobalt-rich deposits; several have grades sufficient for primary cobalt production e.g. Kisanfu (1.1% Co), Mutanda (0.6% Co), Tilwezembe (0.6% Co) (Broughton, 2014; Hitzman et al., 2017).

There is limited reliable data on the size and grade of cobalt resources in marine mineral deposits. Mudd et al. (2013) report 134.0 million tonnes of cobalt in the Clarion-Clipperton Zone of the western Pacific Ocean. However, these estimates should be considered as geological endowment rather than a formal mineral resource with potential for extraction. There are few resource estimates published in compliance with modern reporting codes for marine deposits. A NI 43-101-compliant resource estimate was produced for Nautilus Minerals for part of the Clarion-Clipperton Zone in 2013 (Golder, 2013a). They reported 440 million tonnes of wet ore at 26.9% Mn, 1.2% Ni, 0.24% Co and 1.1% Cu, which equates to approximately 739 000 tonnes of cobalt (based on 30 per cent moisture in ore) (Mudd et al., 2013). Other NI 43-101-compliant resource estimates have been published for different parts of the Clarion Clipperton Zone. Nauru Ocean Resources Inc (NORI) reported 909 million tonnes of wet ore at 29.2% Mn, 1.3% Ni, 1.08% Cu and 0.13% Co in four licence areas covering nearly 75 000 km^2 (Golder, 2013b). This estimate has since been updated for one licence block occupying an area of approximately 25 000 km^2 (AMC Consultants, 2019).

According to the US Geological Survey (2019), the world's total cobalt reserves amount to 6.9 million tonnes. The DRC dominates with approximately half of the total (about 49.5%, 3.4 million tonnes), followed by Australia (17.5%), Cuba (7.3%) and the Philippines (4.1%) (Figure 9).

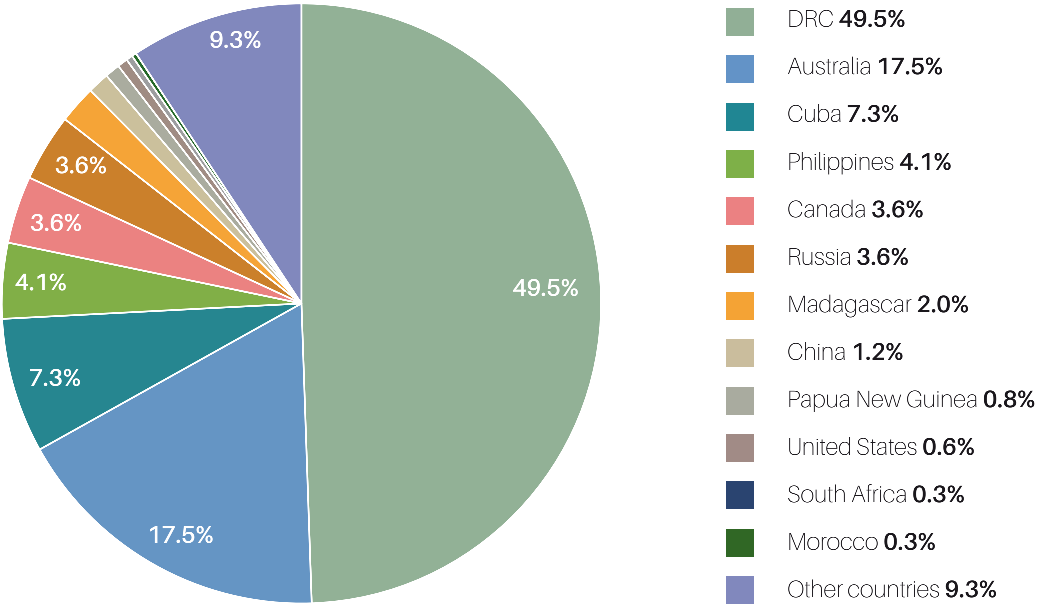


Figure 9 Global cobalt reserves by country. Total reserves amount to 6.9 million tonnes. (Data source: US Geological Survey (2019)).

Supply chain

The global cobalt supply chain (Figure 10) starts with exploration over prospective terranes and around known deposits to identify cobalt resources. This is followed by mining of economic reserves, mostly of copper and nickel from which most cobalt is extracted as a by-product. Only a very small part (about two per cent) of global mine production of cobalt comes from mines that produce cobalt as the main product (Brown et al., 2019; Hitzman et al., 2017). The cobalt is extracted using a range of metallurgical methods dependent on the parent ore type. A range of intermediate and refined cobalt materials is then produced, including cobalt metal. From these, numerous products are manufactured for use in a wide variety of industrial sectors including metal manufacturing, electronics, chemicals, food and biotechnology. The last stage in the value chain comprises the collection of end-of-life (EOL) products and waste and the recovery of cobalt from these sources. Cobalt recovery from industrial and mining wastes, such as tailings and slags, is also becoming increasingly important.

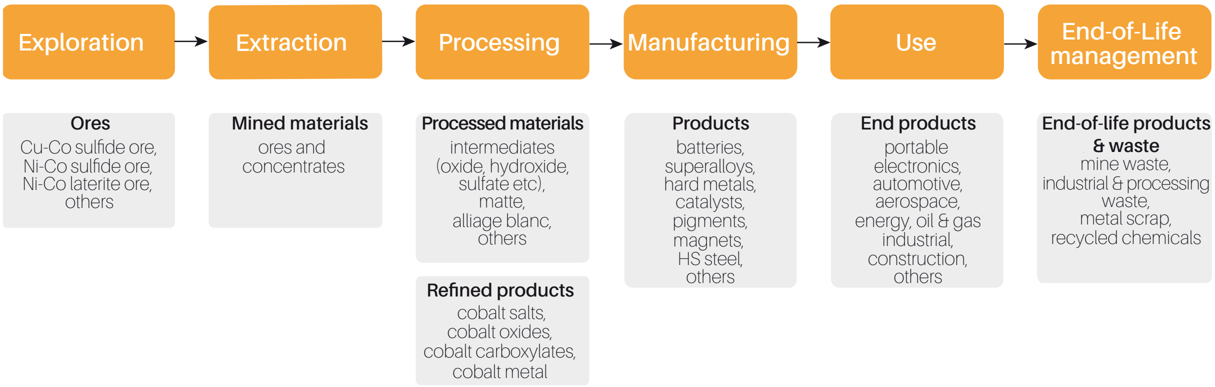


Figure 10 Simplified cobalt supply chain.

Extraction methods and processing for primary ores

Extraction

Depending on their size, grade, morphology and proximity to surface, deposits are mined by open pit methods or underground, or by a combination of both.

Open pit mining: where an orebody is close to the surface (normally less than 100 metres depth), open pit extraction is favoured as it is more cost effective than underground mining. This method typically involves removing the overburden, digging the ore or blasting with explosives, then removing the ore by truck or conveyor belt for stockpiling prior to further processing.

Underground mining: underground extraction uses a variety of standard mining methods depending on the characteristics of the deposit. It is suitable for extraction of higher grade, small or deep ore bodies. Techniques used include block caving (for large, uniform deposits), room and pillar (typically for flat or shallow dipping deposits), and a variety of other methods for narrow or steeply dipping ore bodies.

Open pit and underground mining may be combined at an individual mine, and may take place simultaneously in order to access shallow and deeper parts of an ore body. The open pit mine may be in operation while the underground workings are being developed.

Processing

Cobalt processing technologies are described by Crundwell et al. (2011), Fisher (2011) and Swartz et al. (2009). Cobalt is generally a by-product of copper and nickel extraction; hence their production is commonly linked. About two thirds of global cobalt production is derived from stratiform sediment-hosted copper cobalt deposits, with about 27 per cent from leaching of nickel-cobalt laterites or smelting of nickel sulfides from magmatic sulfide deposits. Much of the remainder is from VMS deposits (Figure 2).

The actual extraction processes used will depend on the type of ore being treated and its composition and on the nature of the required final cobalt product. Other factors taken into account when designing recovery processes include safety and environmental protection, capital and operating costs, optimum efficiency recovery, access to skilled labour, site location and logistics, availability and cost of energy (Fisher, 2011; Peek et al., 2009).

Cobalt is produced and traded in many different forms including concentrates, intermediate compounds, high-purity metal and salts. Pure cobalt metal is produced by two principal processing routes, hydrometallurgy and pyrometallurgy. Hydrometallurgy relies on differences in the solubility and electrochemical properties of different materials. Following leaching, copper is recovered and impurities removed before the recovery of cobalt and, finally, of nickel, if any is present (Fisher, 2011). Pyrometallurgy uses differences in the melting points and densities of materials to separate them. The ore is heated together with a reducing agent to facilitate chemical reactions that separate the metals from other compounds. Some impurities are driven off in gaseous form and others are separated into a slag. After smelting, cobalt normally remains combined with nickel and the two are subsequently separated using electrolytic processes (solvent extraction and electrowinning).

Processing of copper-cobalt sulfide ore

The Central African Copperbelt (CACB) is the main producing region of copper-cobalt sulfides. Weathering in many places has taken place that transformed cobalt-bearing sulfide phases, for example from carrolite (Co_2CuS_4) to heterogenite (CoOOH). The ore mined is from both the weathered zone and from hypogene copper-cobalt sulfides. The processing required to recover cobalt from the weathered and the sulfide ores differs significantly (Figure 11).

In the copper-cobalt weathered ore, whole ore leach (WOL) provides much improved metal recoveries and its use is becoming common practice in DRC. Following crushing and grinding, the ore undergoes reductive leaching using sulphuric acid and sulfur dioxide under atmospheric conditions. The solution produced from this process is separated from unleached solids by counter-current decantation, washing and filtration (Crundwell et al., 2011). The pregnant solution is transferred to solvent extraction for the separation of cobalt and copper. Copper is extracted into an organic extractant and cobalt is left in the aqueous raffinate. The copper-loaded organic phase is sent to electrowinning for the recovery of copper. The cobalt-loaded raffinate undergoes further purification stages to ensure that impurities such as iron, aluminium, manganese, zinc and copper are removed. Following that, cobalt is precipitated from the solution as high-purity cobalt hydroxide using magnesia (MgO) (Crundwell et al., 2011; Fisher, 2011).

For copper-cobalt sulfide, crushing and milling is followed by froth flotation to produce a copper-cobalt concentrate slurry. The slurry is roasted to produce a sulfate calcine, which then follows the same processing steps as the oxide ore of leaching, solid/liquid separation, solvent extraction and precipitation to produce a high purity cobalt hydroxide. Commonly the cobalt hydroxide undergoes re-dissolution and electrowinning to recover cobalt metal.

Alternative technologies may be utilised at different processing stages. For example, the removal of impurities may be carried out by precipitation with limestone and limewater, or ion exchange for removal of zinc, copper and nickel rather than by solvent extraction. Similarly, there are different routes for the precipitation of cobalt to produce various intermediate products, such as cobalt salts, cobalt oxide and hydroxide, and others (Fisher, 2011).

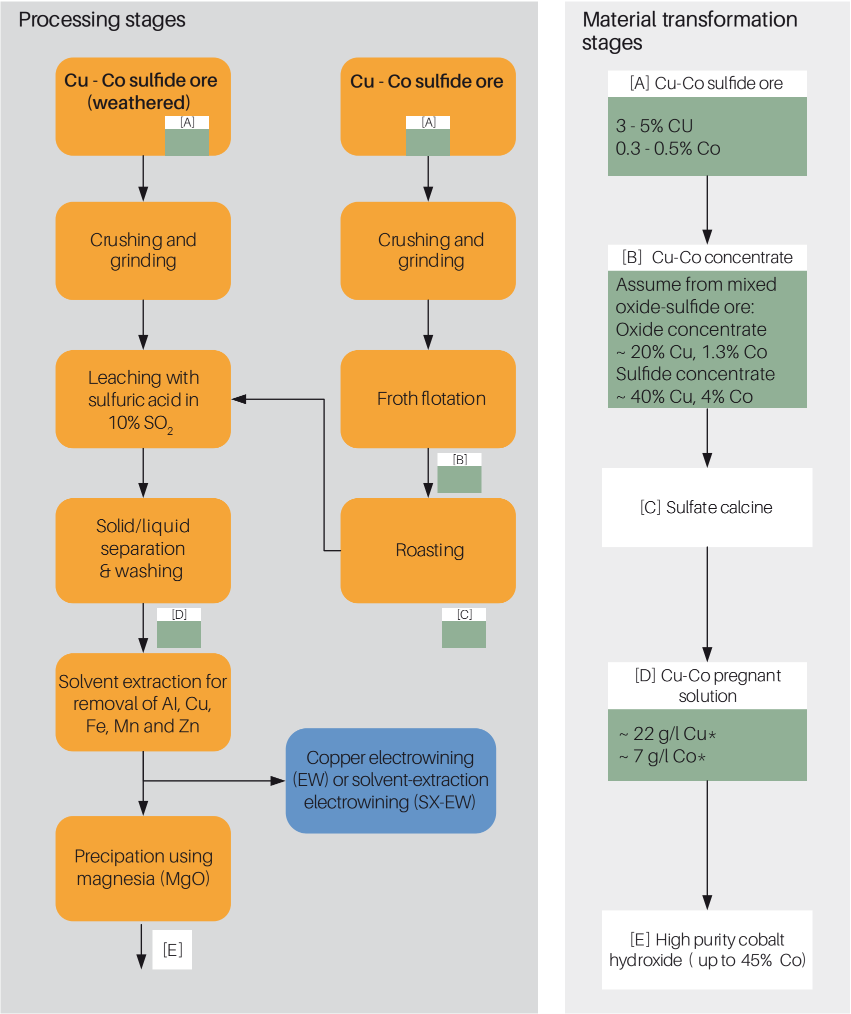


Figure 11 Main processing stages of copper-cobalt ores (constructed using information from Crundwell et al. (2011); Fisher (2011)).

Processing of nickel-cobalt sulfide ore

Cobalt is present in nickel-cobalt sulfide ores either as a cobalt sulfide mineral, such as cobaltite, or in solid-solution in pentlandite. The cobalt recovery process involves crushing and grinding, followed by froth flotation to produce a nickel-cobalt concentrate. The concentrate is subsequently smelted and converted into a low-iron sulfide matte (Figure 12).

There are two options for smelting and converting of nickel-cobalt concentrates to produce matte. These are flash smelting and electric furnace smelting. In flash smelting, the oxidation (conversion) takes place in the furnace together with melting. In the electric furnace, a separate stage of roasting for oxidation is normally included. Flash smelting is more energy efficient than smelting in the electric furnace, but it leads to much greater metal losses to the slag (Roberts & Gunn, 2014).

The converter matte is refined to high purity nickel and cobalt either in a vapour-metallurgical refinery (carbonyl process) or by hydrometallurgy (Crundwell et al., 2011). In hydrometallurgy, the sulfide matte is leached using chlorine in hydrochloric acid, or air in ammonia solutions, or oxygen in sulphuric acid. Cobalt metal is produced by electrowinning or by hydrogen reduction from purified leach solutions (Crundwell et al., 2011).

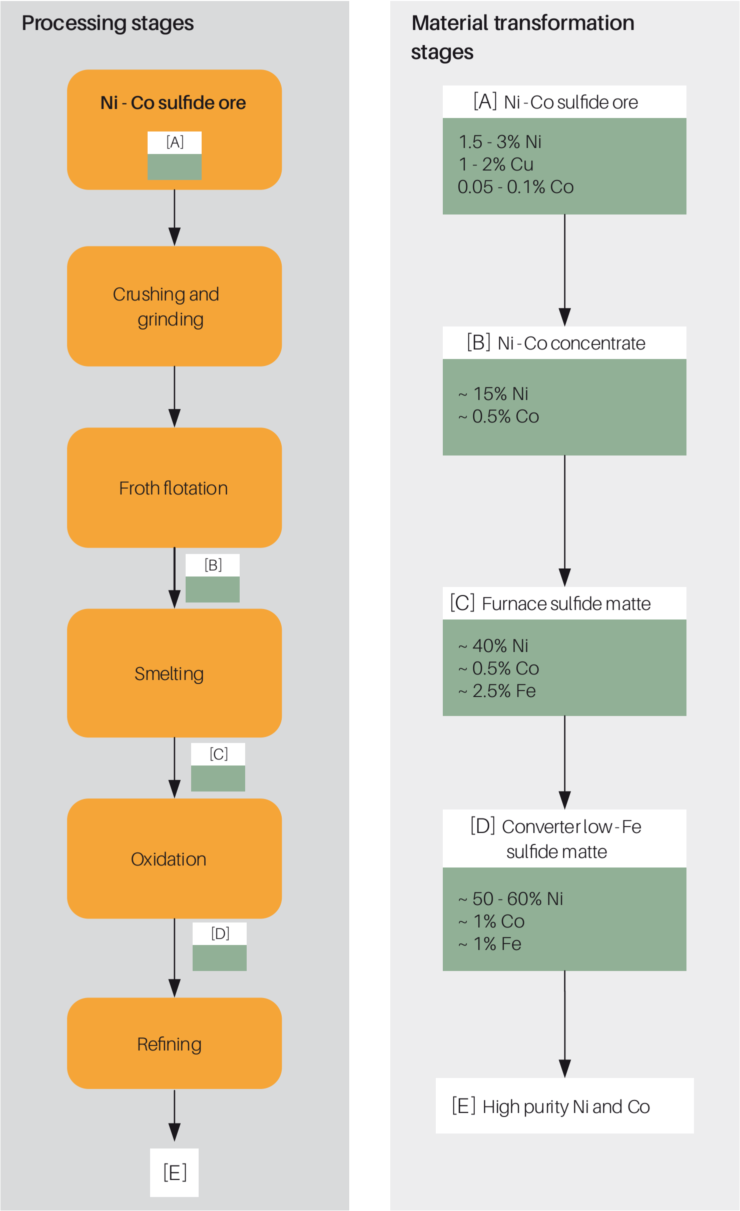


Figure 12 Main processing stages of nickel-cobalt sulfide ores (constructed using information from Crundwell et al. (2011); Roberts and Gunn (2014)).

Several hydrometallurgical processing routes are available as alternatives to smelting of nickel-cobalt concentrates. These involve different process chemistries using ammoniacal, sulfate and chloride routes. These are explained in more detail in Crundwell et al. (2011) and (Fisher, 2011).

Overall, the recovery of cobalt in nickel sulfide smelters varies between 30–80%, which is much less than the typical recovery rates for nickel (97%) and copper (95%) (Roberts & Gunn, 2014).

Processing of nickel-cobalt laterite ore

Nickel laterite ore is commonly smelted to ferronickel, where cobalt is not recovered. However, some nickel laterite ore is smelted to sulfide matte although the cobalt recovery from this matte is inefficient because cobalt oxidises more than nickel and is effectively lost (Crundwell et al., 2011).

In contrast, cobalt is commonly extracted as a by-product from the limonite and smectite layers of the laterite ore by leaching at high temperature and pressure with sulfuric acid (high pressure acid leaching, HPAL, in an autoclave at 250°C, 40 bar pressure) (Figure 13). Following leaching, the ore is cooled through flash tanks where energy recovery takes place. The cooled slurry undergoes pre-neutralisation and solid - liquid separation. The impure leach solution is neutralised and purified to remove more contaminants. Nickel and cobalt are precipitated as a mixed nickel-cobalt sulfide using hydrogen sulfide gas (Crundwell et al., 2011; Roberts & Gunn, 2014). There are several alternatives to mixed sulfide precipitation, including the precipitation of nickel carbonate, direct solvent extraction and precipitation of nickel-cobalt hydroxides (Crundwell et al., 2011). Refining of the nickel-cobalt sulfide is undertaken primarily by hydrometallurgy, where different refineries have established distinct processes to suit their feed material.

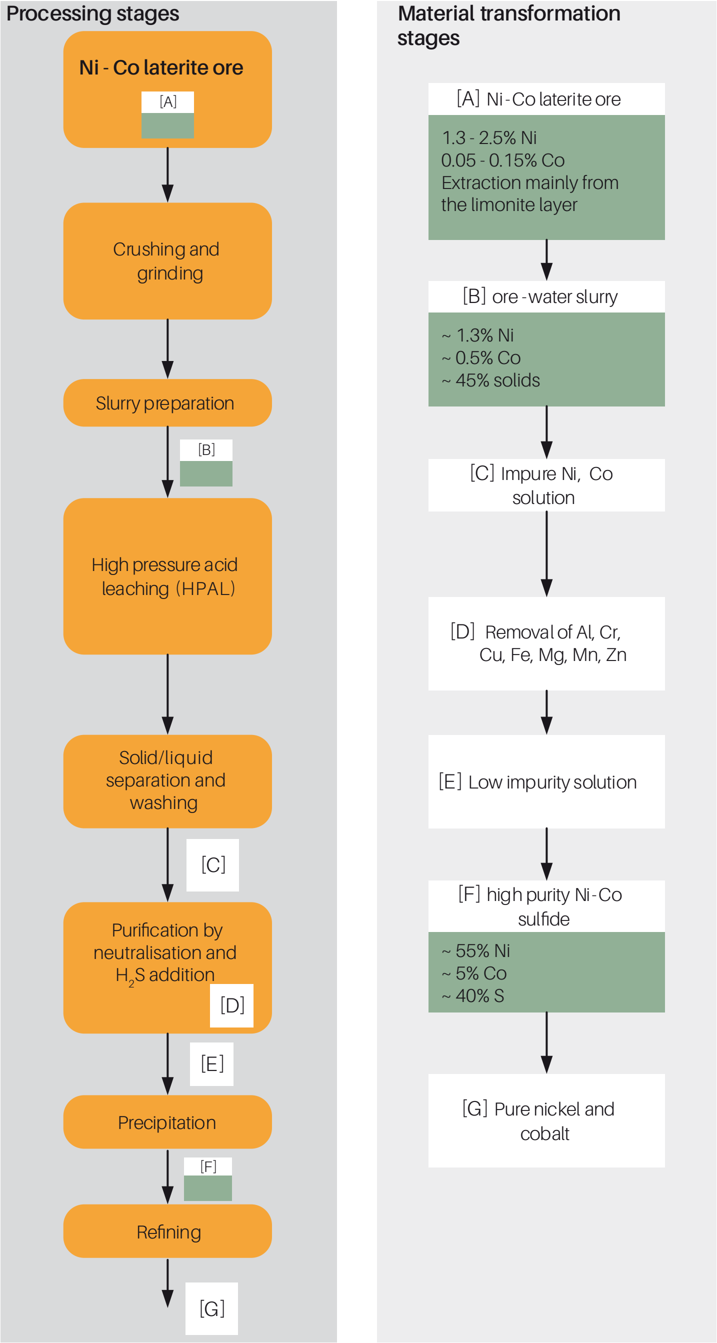


Figure 13 Main processing stages of nickel-cobalt laterite ores (constructed using information from Crundwell et al. (2011); Roberts and Gunn (2014)).

Other processing technologies

Improvements to conventional heap-leach (HL) technology, which is cheaper to set up and operate than high-pressure acid leaching (HPAL) or smelter operations, may lead to its increased use for the recovery of cobalt. The HL technology process generally involves (Petersen, 2016):

- crushing and agglomeration of ore;
- development of heaps by placing ore on a lined pad and irrigating with the appropriate lixiviant to dissolve metals (leachate);
- collecting leachate in a pond or tank (pregnant leach or value bearing solution - PLS);
- processing pregnant solution to recover metals; and
- recycling barren solution (with additional lixiviant) back to the heap.

Some previously uneconomic, low-grade deposits may be amenable to some form of heap leaching for the extraction of cobalt. For example, Çaldağ Nikel is planning to use atmospheric tank leaching to produce a slurry from which nickel and cobalt will be recovered by solvent extraction and electrowinning (Çaldağ Nikel, 2014). A method for the recovery of cobalt from nickel laterites using heap leaching is also described in a patent document (Purkiss & Anthony, 2004).

Bioprocessing technologies can provide alternative routes for the recovery of cobalt. Bioleaching has been used to recover cobalt from the pyrite-rich mine tailings from the Kilembe sulfide deposit in Kasese, Uganda (KCCL, 2018; Morin & d'Hugues, 2007). Tailings were bioleached in stirred tanks at approximately 40°C in the presence of acidophilic bacteria and archae (a domain of single-celled organisms) that caused the oxidative dissolution of pyrite and cobalt associated with the pyrite. Cobalt was further recovered by solvent extraction and electrowinning (Morin & d'Hugues, 2007; Smith et al., 2017). Bioleaching under ambient pressure and temperature has also been successfully implemented at the Talvivaara (now Sotkamo) deposit in Finland (Riekkola-Vanhanen & Palmu, 2013). Recent research has also been investigating the use of bioprocessing technologies in cobalt-bearing limonitic laterites (Smith et al., 2017).

Purification by solvent extraction (SX) and ion exchange (IX) have gained popularity, particularly when the production of cobalt metal products is the aim. The Chambishi Metals refinery in Zambia is the only one employing solvent extraction and ion exchange in the CACB. The process involves the precipitation of iron, aluminium and residual copper and the removal of zinc and manganese by solvent extraction. Cobalt hydroxide is then precipitated using lime. Following that, the cobalt hydroxide is redissolved in acidic spent electrolyte from cobalt electrowinning and nickel is removed by ion exchange leaving a purified cobalt advance electrolyte. The final step of the process involves the recovery of cobalt by electrowinning (Sole et al., 2019; Swartz et al., 2009). The use of ion exchange has a number of advantages over other methods: it can produce higher purity cobalt electrolytes; it does not use toxic or flammable solvents; and the process is easy to control and automate. The combination of SX and IX processes may find further use in the CACB in the near future (Sole et al., 2019).

Refining

Refined cobalt products are traded in various forms including metal and cobalt salts, oxides and carboxylates. Cobalt metal is available in powders, granules, briquettes, cathodes, rounds, pellets and ingots. Cobalt salts include a large range of products, such as chlorides, sulfates, nitrates, carbonates, acetates and many more. Cobalt oxides and hydroxides are produced alongside cobalt salts in chemical refineries.

The cobalt salts are derived from a variety of refining steps. For example, cobalt cathode is produced by electrowinning, but practical issues associated with solution purification requirements and plating of cobalt onto the stainless steel cathode blanks have led to the development of alternative production methods. Cobalt rounds are an alternative to cobalt cathodes where cobalt is deposited by electrowinning on the exposed round area of stainless steel disks and is easily stripped (Fisher, 2011; Vale, 2016). Other products, such as cobalt metal in the form of briquettes and powders, are produced by hydrogen reduction in an autoclave. Cobalt sulfate is produced via steps of evaporation and crystallisation; cobalt sulfide can be precipitated using sodium hydrosulfide (NaHS) or hydrogen sulfide (H_2S); and cobalt hydroxide is produced through precipitation with magnesia and lime (Fisher, 2011; Sole et al., 2019; Swartz et al., 2009).

Factors such as the deposit type, market, supply chain and availability of processing and refining capacity dictate the refined cobalt products actually made. For example, nickel-cobalt concentrate from the Glencore-owned mines in Canada is processed in the nearby Sudbury smelter, which produces a nickel-cobalt matte. This matte is refined into pure metal in Norway, in the Glencore-owned Nikkelverk refinery. Most of the African copper-cobalt sulfide concentrate is processed ‘in-house’ to produce an impure cobalt hydroxide. This is then shipped to China’s chemical refineries, where a range of cobalt salts including cobalt oxide and hydroxide are produced for use in multiple applications.

The cobalt content of some cobalt products is presented in Table 4.

Table 4 Common cobalt products and their chemical cobalt specification. (Data sources: Cobalt Institute (2019a); Freeport Cobalt (2019); Huayou Cobalt (2019); Sole et al. (2019)).

Cobalt product	Cobalt content (%)	Material form
LME traded cobalt	≥99.8	Cobalt metal: cathode (broken or cut), ingots, briquettes, rounds
Cobalt sulfate	≥21	Cobalt compound ($CoSO_4.7H_2O$)
Cobalt carbonate	≥45	Cobalt compound ($CoCO_3$)
Cobalt chloride	≥24	Cobalt compound ($CoCl_2.6H_2O$)
Cobalt hydroxide	≥62	Cobalt compound ($Co(OH_2)$)
Cobalt oxide	≥72	Cobalt compound (Co_3O_4)

Uses

Cobalt uses can be divided into two main groups: metallurgical applications (market share 37 per cent in 2017); and chemical applications (market share 63 per cent in 2017). The main end use applications for cobalt are shown in Figure 14.

Cobalt metal, oxide and hydroxide are used in the production of the cathode in rechargeable batteries. Lithium-ion batteries (LIBs) are a very important market at present due to their high energy

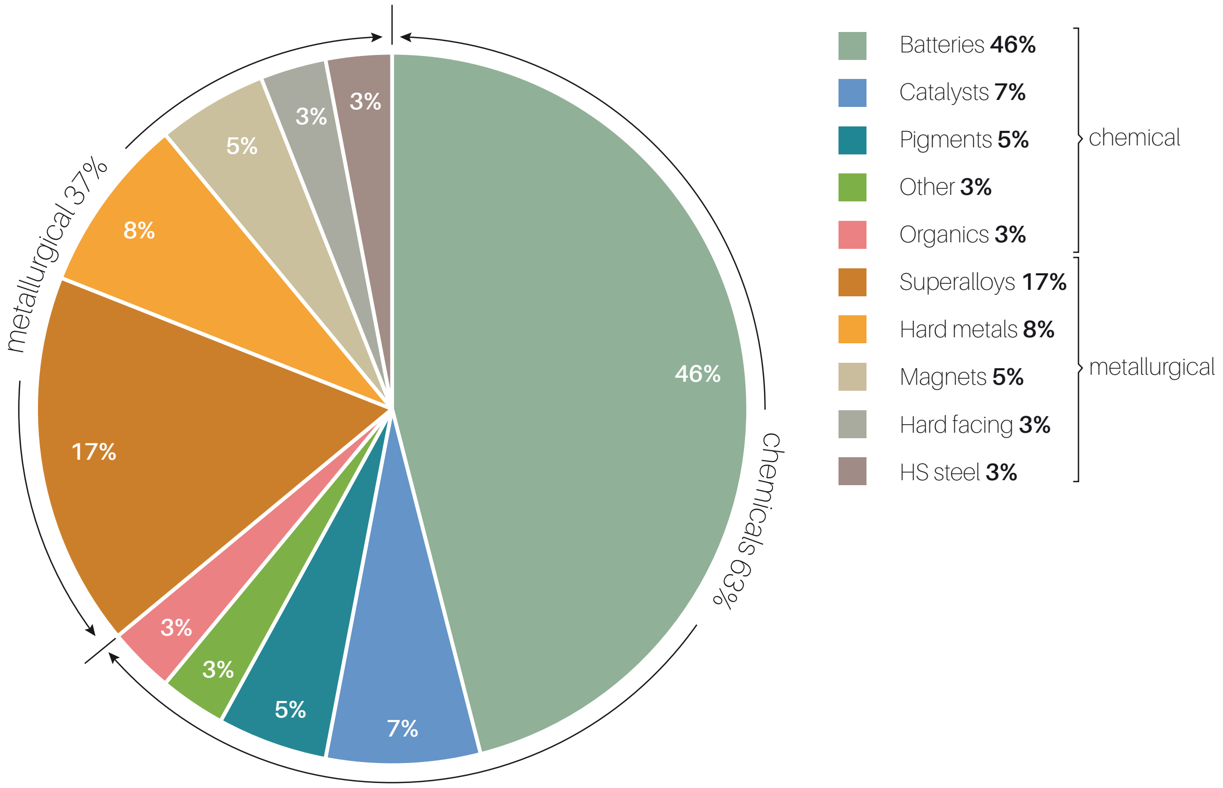


Figure 14 Global cobalt consumption by application in 2017 (%) (Data source: Cobalt Institute and Roskill (2018)).

and power density and a greater proportion of cobalt is used in them than for any other purpose. LIBs are used in portable electronics, medical devices and electric vehicles as well as for energy storage. Various classes of LIBs of differing chemistries are currently in use. For example, the cathode of a lithium-cobalt oxide (LCO) battery consists primarily of cobalt, whereas the lithium-nickel-manganese-cobalt oxide (NMC) class 111 battery contains equal amounts of nickel, manganese and cobalt (Gunn & Petavratzi, 2018). Cobalt is used in several other battery technologies, including nickel-cadmium batteries (NiCd) and nickel-metal hydride (NiMH) batteries. The usage of cobalt in these batteries is small (Cobalt Institute, 2019b).

Cobalt metal is used in a range of alloys, including superalloys, magnetic alloys, prosthetic alloys and wear-resistant alloys. Superalloys are used in the aerospace sector, in nuclear reactors, power plants and in chemical equipment where resistance to elevated temperature and high surface stability are required. Cobalt-chrome alloys are employed in hip and knee replacements and in dental implants (Cobalt Institute, 2019b).

Cobalt is also used in magnets, which are utilised in products such as wind turbines, hard disk drives, motor sensors, actuators and magnetic resonance imaging. Permanent cobalt-bearing magnets include: the aluminium-nickel-cobalt range used in motors and sensors; samarium-cobalt magnets used in instrumentation, electronics and motors; and neodymium-iron-boron magnets, which include cobalt as a coating element.

Another important application of cobalt is in the hardmetal (cemented carbide) industry for the production of hard-wearing cutting and grinding tools. The hardmetal comprises carbide particles bonded together by a metallic binder. Cobalt is commonly used as a binder for tungsten carbide in a wide variety of components and tools utilised by the automotive, aerospace, energy, mining and general engineering sectors.

A wide variety of cobalt compounds, including metal, oxide, sulfate, hydroxide and diacetate, is used in catalysts in desulfurisation processes during the manufacture of natural gas and refined petroleum products. Another important use of cobalt catalysts is in the synthesis of precursors used in the creation of PET (polyethylene terephthalate) plastics. Cobalt catalysts are also employed in the production of aldehydes from alkenes in the OXO reaction process. These are used by the chemical industry to manufacture products such as perfumes (Cobalt Institute, 2019c).

Various cobalt salts have long been used as pigments to impart a vivid blue colour to pottery, enamels, inks and glass. This use continues today, accounting for about five per cent of cobalt consumption in 2017 (Figure 14). Cobalt metal and various compounds, such as cobalt antimony, cobalt boron, cobalt germanium and others, are used in numerous electronic products that contain integrated circuits, processors, digital storage and semi-conductors. Cobalt also has a range of applications in healthcare, including: measurement of vitamin B12 absorption and diagnosis of vitamin B12 deficiency; detection of tumours and metastases; radiotherapy treatment of cancer; and sterilisation of medical equipment (Cobalt Institute, 2019b).

Health and the environment

Cobalt occurs naturally in the environment where, at high concentrations relative to background levels, it can have detrimental effects. Elevated concentrations of cobalt are associated with both natural processes, for example weathering of rocks, breakdown of organic matter and volcanic eruptions, and with anthropogenic activities, such as mining, refining and metal manufacturing, chemical manufacturing and agriculture. Prevention and mitigation actions for avoiding adverse impacts to the environment and human health will be case specific. These depend on the industrial activities or natural processes taking place, the regulatory framework, the prevailing cobalt concentrations and the form in which the cobalt occurs.

The availability of cobalt in the aquatic environment, soil, food and the atmosphere depends on several factors. These are commonly associated with the physico-chemical conditions of the environment itself, such as pH, water hardness, organic matter concentration and temperature (Cobalt Institute, 2019d; Slack et al., 2017). Cobalt in the aquatic environment, whether derived from anthropogenic or natural sources, may bind with suspended solid materials and ultimately be deposited in sediments on the sea or lake floor.

Geochemical baseline data collected from stream sediments, water and soil provide important information to understand environmental change. At the European level, the Geochemical Atlas of Europe (FOREGS), produced through the collaboration of several geological surveys, provides environmental geochemical baseline data (FOREGS, 2019). Similar databases also exist at the national level: for example, in the UK, the geochemical baseline survey of the environment (G-BASE) project provides maps showing the distribution of many elements, including cobalt (British Geological Survey, 2019).

In the atmosphere, cobalt may be released from flue gases associated with industrial activities, but these are generally well regulated and controlled. Cobalt may also exist in dust released to the air from transport and industrial processes, including mining. A small proportion of cobalt in the atmosphere is derived from natural sources such as volcanic eruptions and weathering.

Under weathering conditions cobalt is dissolved from its host minerals, such as sulfides and arsenides, and commonly occurs in the +2 and +3 oxidation states as complexes with hydroxide, fluoride, sulphate, phosphate, chloride and organic material (Slack et al., 2017). Dissolution of cobalt-bearing sulfides can be associated with acid mine drainage (AMD), which can have significant environmental consequences (Slack et al., 2017). AMD is an important issue if it is not appropriately contained and managed.

Cobalt is essential for living organisms, including plants, animals and humans. Humans, for example, need it in the form of vitamin B12. However, exposure to cobalt at high levels may cause a range of harmful effects, ranging from allergic skin reaction, asthma symptoms and breathing difficulties to cancer, damage to organs or even death, if inhaled (ECHA, 2019). Various studies in the literature have examined the effect of cobalt on animals, humans and plants under a range of exposure levels and routes, for example inhalation, oral intake and skin contact (Cobalt Institute, 2019e; ECHA, 2019; IARC, 2006; Sauni et al., 2017). The results vary considerably especially regarding the carcinogenicity of cobalt to humans. Factors such as the type of industry under investigation, the number of workers involved in the study, the time period in the analysis, potential exposure to other compounds and the underlying health conditions of the cohort all influence the results of epidemiological and cohort studies. The 14th report on carcinogens states that cobalt and cobalt compounds that release cobalt ions in vivo are anticipated to be human carcinogens (US Department of Health and Human Services, 2016). The International Agency for Research on Cancer (IARC) has evaluated four groups of cobalt compounds: cobalt and cobalt compounds; cobalt metal with tungsten carbide; cobalt metal without tungsten carbide; and cobalt sulfate and other soluble cobalt (II) salts. They are all classified as 'possibly carcinogenic to humans' (IARC, 2006). Furthermore, the EU harmonised classification and labelling system defines a variety of cobalt substances to have carcinogenic potential for humans (Cobalt Institute, 2019e; ECHA, 2019). Systematic exposure to cobalt can increase the number of red blood cells produced by the body (hypoxia) and certain cobalt substances may cause allergic reactions, such as allergic contact dermatitis (ACD), rash or eczema (Cobalt Institute, 2019e).

A recent biomonitoring study of artisanal miners in the DRC found that they had much higher levels of cobalt in urine and blood than people not involved in mining living in a nearby control area (Nkulu et al., 2018). In addition, the study highlights that the differences were greater for children involved in ASM, where there was evidence of exposure-related oxidative DNA damage. The main pathway for the excessive intake of cobalt was found to be dust emissions. The authors suggest that high exposure of cobalt in the longer term may have adverse impacts to the heart, lung, blood and thyroid, whilst the increased oxidative DNA damage found in children may resulted to increased risk of cancer in later life (Nkulu et al., 2018).

World production

Global cobalt mine production in 2017 amounted to nearly 139 000 tonnes (Brown et al., 2019). The DRC dominates with a share of 59 per cent of total production in 2017. Other significant current producers include New Caledonia (seven per cent), China (six per cent), Canada (five per cent), Australia (four per cent), Cuba, Papua New Guinea, Zambia, Madagascar, Philippines, Finland, Russia and Morocco (Figure 15). Cobalt produced in the DRC and Zambia is a by-product of copper extraction from stratiform sediment-hosted copper-cobalt deposits, while cobalt mine production in most other countries is a by-product of nickel mining. For example, in Cuba and New Caledonia cobalt is a by-product of nickel extraction from laterite deposits, while cobalt produced in Canada, Russia and China is from magmatic sulfide deposits. Cobalt is produced as the primary commodity from only a single operating mine, which is located at Bou Azzer in Morocco.

Between 1993 and 2017 mine production of cobalt increased at a compound annual growth rate of seven per cent (BGS World Mineral Statistics Database). In most years between 1993 and 2001 global mine production of cobalt was in the range 20 000–40 000 tonnes. Since then production has grown rapidly, although DRC has maintained its position as the dominant global producer for several decades. The annual production level in the DRC in 2017 was almost 40 times greater than it was in 1993. China has also recorded a major increase in production in recent years. There was no reported mine production in China before 1983, while in 2017 its production was 9000 tonnes (six per cent of the global total). Elsewhere significant increases in production have been recorded in New Caledonia, Australia, Canada and Europe. Between 1970 and 2017 the number of countries reporting mine production of cobalt has increased from eight to 22.

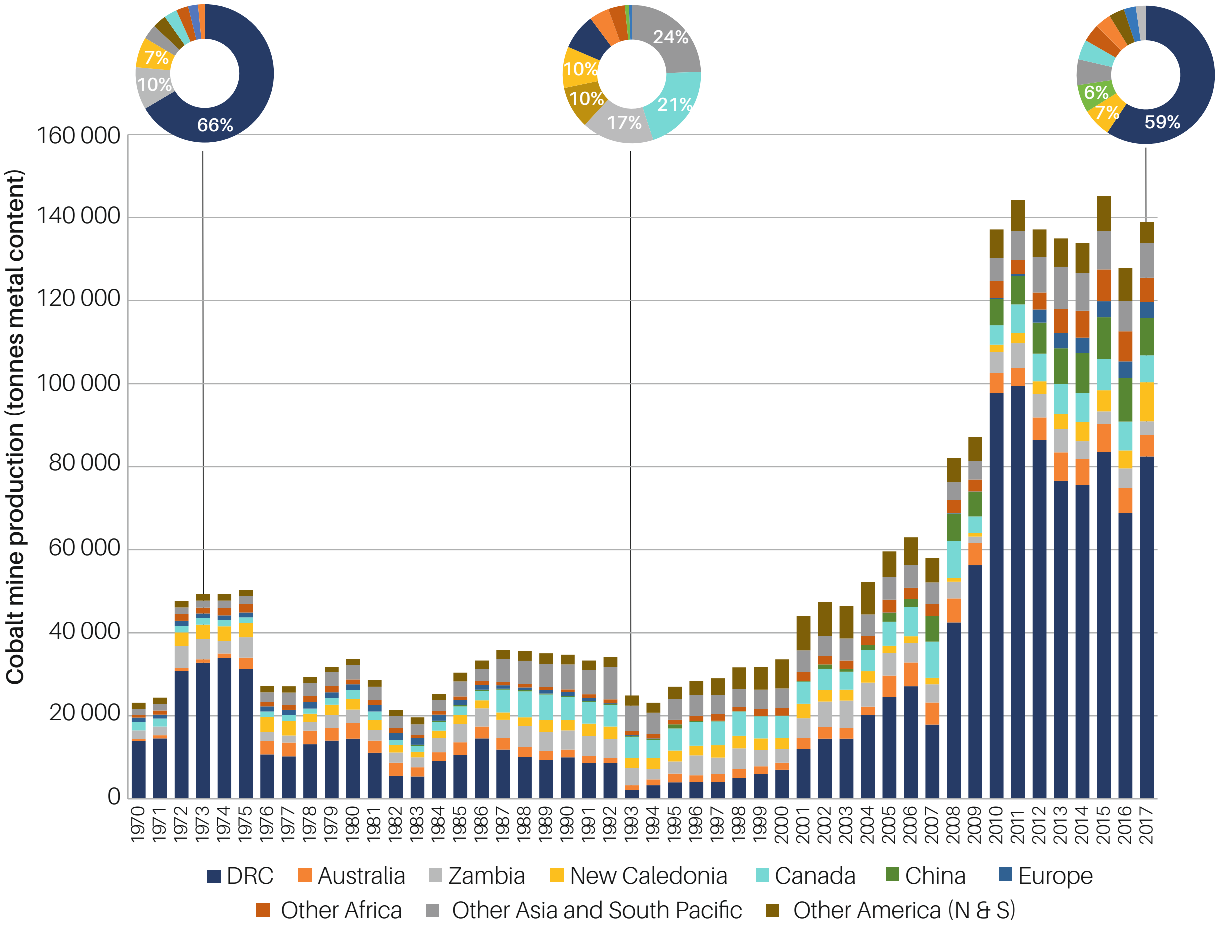


Figure 15 The distribution of global mine cobalt production from 1970 to 2017. (Data source: British Geological Survey World Mineral Statistics Database).

Obtaining a world total for refined cobalt production is complicated by the many different forms that cobalt is refined into, as shown in Table 4. Cobalt is moved around the world in 'intermediate' forms that are subsequently further refined and consequently the risk of double counting is considerable. Material that is considered by one country as 'finished' may simply be a 'feed' material in another. However, despite these difficulties, it is clear that, in contrast to mine production, refined cobalt production is dominated by China, which produced more than 60 per cent of the world total in 2017 (BGS World Mineral Statistics Database). Other major sources of refined cobalt are Finland (ten per cent), Belgium (six per cent), Canada (five per cent) and Japan (four per cent) (Figure 16). About 36 per cent of the global refined cobalt production is based on imported material processed by countries that have no indigenous cobalt mine production, for example, Belgium (Roberts & Gunn, 2014). In Europe, almost all of the refined cobalt in various forms is derived from imported materials (European Commission, 2017b).

Throughout the 1970s and 1980s global production of refined cobalt averaged approximately 20 000 tonnes per annum. Since 1993 the world total has increased rapidly at a compound annual growth rate of eight per cent (BGS World Mineral Statistics Database). There have been a number of conspicuous changes in the production levels and global shares of production in the past 25 years. Most dramatic is the increase in China with reported production of 750 tonnes in 1993 rising to 69 600 tonnes in 2017. In 1993 China accounted for about five per cent of the global total. This rose sharply in the following years, to 11 per cent in 2003, 32 per cent in 2008 and 58 per cent in 2017. There has also been a sharp rise in production in Finland from 2200 tonnes in 1993 to 12 200 tonnes in 2017. Other countries that have shown marked increases over the same 25-year period include Japan, South Africa and Norway. New producers of refined cobalt include Madagascar and New Caledonia where production commenced in 2012. Refined cobalt production was strongly concentrated in the DRC throughout the 1970s when it provided more than 50 per cent of the global total. Thereafter the DRC share reduced gradually until the early 1990s. After 1992 its share fell rapidly and since 2001 it has not exceeded nine per cent of the global total. Production in Russia has fallen significantly with production of 5000–6000 tonnes per annum during the 1980s to about 2000 tonnes in 2017.

The Responsible Minerals Initiative reference list includes 32 cobalt smelters in 8 countries (RMI, 2019b). Of these 22 are located in China and the remainder in South Korea, Australia, Norway, Finland, Belgium, Morocco and Canada. Cobalt smelters are also known to exist in other countries (Figure 17). In 2017, there were 16 countries that reported production data for refined cobalt (BGS World Mineral Statistics Database). This compares with 12 countries in 1993 and ten throughout most of the 1970s and 1980s.

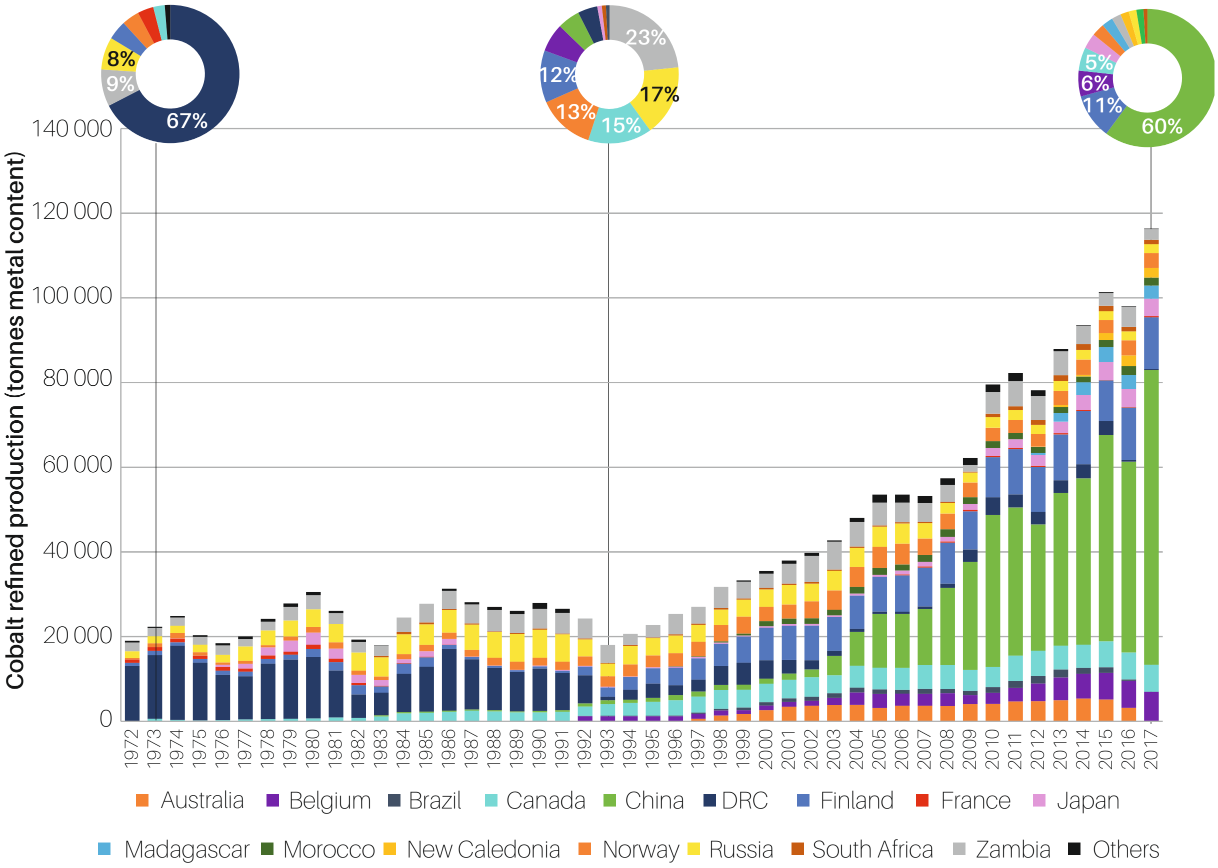
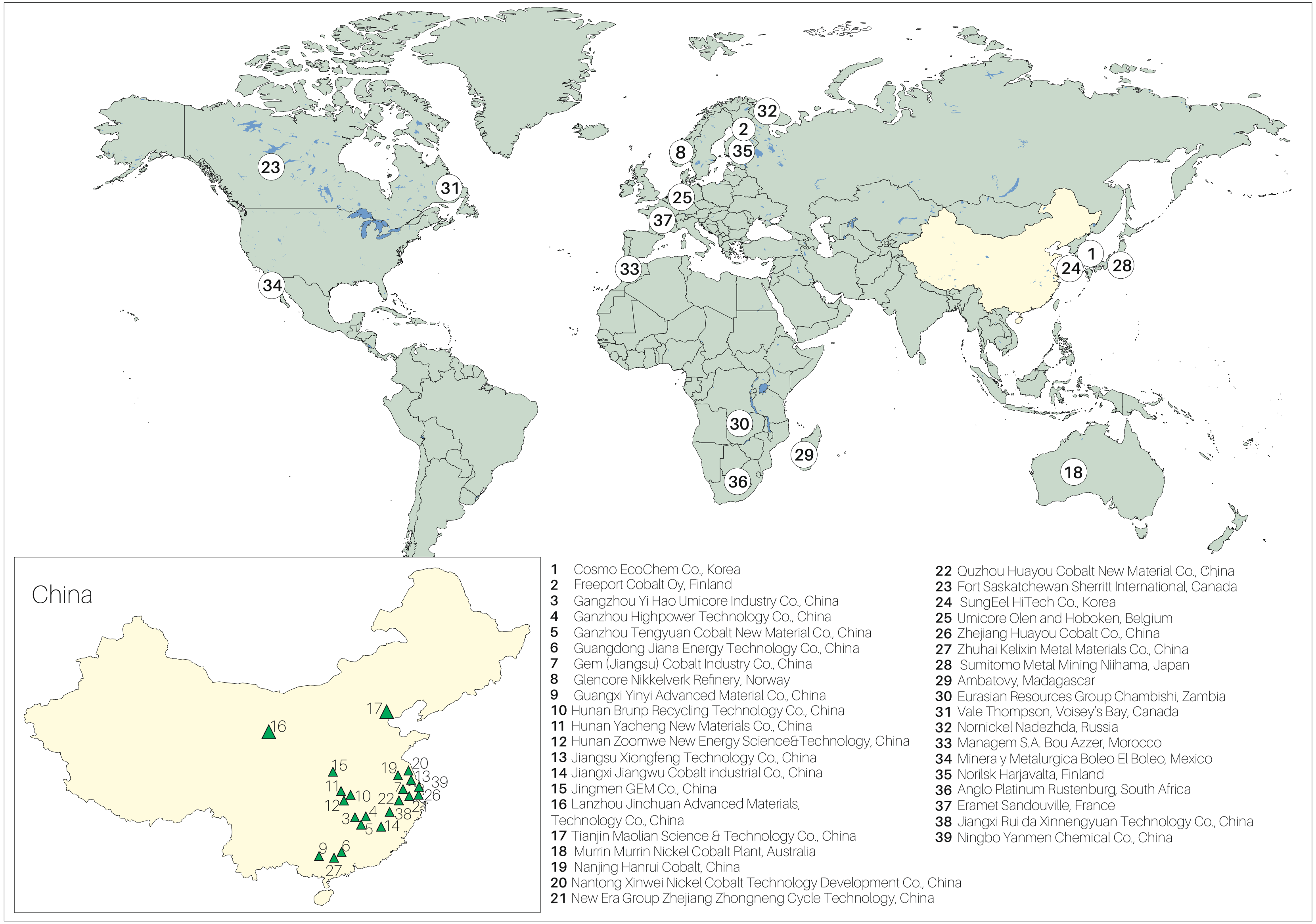


Figure 16 The distribution of global refined cobalt production from 1972 to 2017. 'Others' includes Albania, Czech Republic, Germany, India, Uganda and USA. (Data source: British Geological Survey World Mineral Statistics Database).



1 Cosmo EcoChem Co., Korea
2 Freeport Cobalt Oy, Finland
3 Gangzhou Yi Hao Umicore Industry Co., China
4 Ganzhou Highpower Technology Co., China
5 Ganzhou Tengyuan Cobalt New Material Co., China
6 Guangdong Jiana Energy Technology Co., China
7 Gem (Jiangsu) Cobalt Industry Co., China
8 Glencore Nikkelverk Refinery, Norway
9 Guangxi Yinyi Advanced Material Co., China
10 Hunan Brunp Recycling Technology Co., China
11 Hunan Yacheng New Materials Co., China
12 Hunan Zoomwe New Energy Science&Technology, China
13 Jiangsu Xiongfeng Technology Co., China
14 Jiangxi Jiangwu Cobalt industrial Co., China
15 Jingmen GEM Co., China
16 Lanzhou Jinchuan Advanced Materials, Technology Co., China
17 Tianjin Maolian Science & Technology Co., China
18 Murrin Murrin Nickel Cobalt Plant, Australia
19 Nanjing Hanrui Cobalt, China
20 Nantong Xinwei Nickel Cobalt Technology Development Co., China
21 New Era Group Zhejiang Zhongneng Cycle Technology, China
22 Quzhou Huayou Cobalt New Material Co., China
23 Fort Saskatchewan Sherritt International, Canada
24 SungEel HiTech Co., Korea
25 Umicore Olen and Hoboken, Belgium
26 Zhejiang Huayou Cobalt Co., China
27 Zhuhai Kelixin Metal Materials Co., China
28 Sumitomo Metal Mining Niihama, Japan
29 Ambatovy, Madagascar
30 Eurasian Resources Group Chambishi, Zambia
31 Vale Thompson, Voisey's Bay, Canada
32 Nornickel Nadezhda, Russia
33 Managem S.A. Bou Azzer, Morocco
34 Minera y Metalurgica Boleo El Boleo, Mexico
35 Norilsk Harjavalta, Finland
36 Anglo Platinum Rustenburg, South Africa
37 Eramet Sandouville, France
38 Jiangxi Rui da Xinnengyuan Technology Co., China
39 Ningbo Yanmen Chemical Co., China

Figure 17 Selected cobalt smelters worldwide (Data sources: DERA (2019); RMI (2019b)).

Supply from artisanal mining

Artisanal and small-scale mining (ASM) is an important contributor to cobalt supply. The DRC is the largest producer of cobalt globally and, according to estimates from the DRC government, about 20 per cent of exported cobalt comes from artisanal mining in the southern part of the country (Amnesty International, 2016). Other sources report that up to 40 per cent of the cobalt mined in DRC is produced by ASM (Sanderson, 2019; Trafigura, 2018). The number of artisanal copper-cobalt miners in the DRC is estimated to be about 200 000. They commonly extract cobalt from small sites located alongside large-scale industrial operations (Trafigura, 2018). Cobalt extraction in artisanal mines is not mechanised and generally involves digging pits to access the ore or handpicking cobalt ore from mine tailings. The ore undergoes some initial preparation that includes washing, screening and sorting to remove impurities. It is subsequently sold to independent traders who, in turn, sell it to larger companies that are able to further process and refine the ore (Amnesty International, 2016).

The mining code in the DRC requires ASM to take place within authorised zones (artisanal mining zones or ZEAs), where industrial mining is not viable (Amnesty International, 2016). A revision to the code in 2018 introduced further restrictions, by barring individuals from owning mineral rights and allowing concessions only between legally recognised groups and the state. In addition, artisanal miners should be of Congolese nationality (Zeuner, 2018). Although these requirements contribute to the development of a legal framework to regulate ASM, they are also very restrictive and often result in informal and unregulated ASM activities, as many local communities rely heavily on ASM to sustain a living (Amnesty International, 2016). The state regulator in the DRC for ASM is SAEMAPE (Service for Assistance and Supervision of Artisanal and Small-Scale Mining), who are responsible for monitoring formal ASM activities (SAEMAPE, 2019).

ASM makes an important contribution towards economic development and poverty mitigation in many local communities in the DRC. Individuals, small groups and larger groups operating in cooperatives conduct ASM following either formal or, commonly, informal (unregulated) procedures (Amnesty International, 2016; Trafigura, 2018). There have been many reports concerning human right abuses, the use of child labour and health and safety impacts on ASM miners. Various environmental and social problems have also come to light (Callaway, 2018; Nkulu et al., 2018; Ross, 2019; Sanderson, 2019; Zeuner, 2018).

The repeated claims in the media and in NGO reports of human rights abuses related to artisanal mining of cobalt, together with consumer pressure for responsible sourcing (see also section on responsible sourcing) and the need to maintain production from artisanal projects, has led to the development of controlled ASM projects supported by large mining producers. For example, the Mutoshi Cobalt project, supported by Chemaf and Trafigura, aims to enhance ASM activity on the Mutoshi concession so that it can become formalised and semi-mechanised (Trafigura, 2019). Chemaf appointed an ASM contractor (COMIAKOL) and Pact, an NGO specialising in artisanal mining, to develop this pilot project on behalf of about 5000 miners. Workers in this project, who must be at least 18 years old, are provided with identity cards and must register with COMIAKOL. They are only allowed to work within demarcated zones, are provided with personal protective equipment and are able to work under secure and safe conditions. They are only allowed to dig vertical pits that are less than 10 metres deep. The extracted ore is washed in defined mineral washing basins and securely transported by COMIAKOL to a single Chemaf-operated buying station. Following assaying and analysis the cobalt ore is transported to a dedicated standalone facility at the Chemaf Usoke plant for the production of cobalt hydroxide. The ASM cobalt ore is kept separate from Chemaf's large scale mined ore at all times (Trafigura, 2019).

Other initiatives, such as Daimler's decision to join China's Responsible Cobalt Initiative and address social and environmental issues across the whole supply chain, suggest that ASM is increasingly important for the supply of cobalt and is taken into account by the manufacturing sector (Sun, 2018).

Figure 18 Artisanal mining zone (ZEA, Zone d`exploitation artisanale) in Kasulo, near Kolwezi, Lualaba Province, DRC. (Photo courtesy of Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)).

With the electrification of our energy systems, demand for cobalt is projected to increase. ASM has already proven to be a significant source of supply, while, at the same time, providing important revenues to local communities. Actions taken to ban ASM may reduce human rights abuses, health impacts and child labour, but, at the same time, are likely to be detrimental to the ASM miners, who rely on this to sustain their livelihood. Such interventions may also contribute to tension and conflict between ASM and industrial mining projects (Callaway, 2018; Katz-Lavigne, 2019; Transport & Environment, 2019; Zeuner, 2018). Creating effective synergies and collaborations between ASM, industrial mining projects, the government and manufacturing firms that rely on secure cobalt supply could build a safe and secure environment for ASM to develop into more formalised and sustainable mining operations.

Supply from secondary materials

Supply of cobalt from mining and refining waste

Given that most cobalt is a by-product of the extraction of copper or nickel, the metallurgical processing is not optimised for cobalt recovery. As a result a significant proportion of cobalt ends up in tailings and slags after ore processing and refining. For example, it is estimated that between 40 per cent and 60 per cent of the cobalt content of the ores is lost during the concentration process. Furthermore, the overall recovery of cobalt from nickel sulfide ores is estimated to be about 40 per cent with smelting being the least efficient stage in the processing route (Crundwell et al., 2011).

Cobalt in tailings and slags may constitute a potentially large resource. For example, tailings from several historic mining projects in the CACB have high cobalt potential:

- The Lubumbashi Big Hill project, which ceased operation in 2017, had a capacity to produce up to 5500 tonnes of cobalt. The operation processed slag and produced alliage blanc (cobalt-bearing alloy) at the Big Hill smelter (Al Barazi et al., 2017; Mining Dot Com, 2018; Roskill, 2017).

- The Kipushi cobalt–copper tailings project, which is currently under development, involves the reprocessing of copper-cobalt tailings from the Kipushi Tailings Storage Facility (TSF). The project is operated by Soludo Lambert Mining SAS, under a 50/50 joint venture arrangement between Paragon Mining SARL and Cape Lambert. Cape Lambert Resources has recently published a JORC-compliant indicated resource estimate with copper-cobalt tailings of 2.3 million tonnes at 0.33% Co and 1.0% Cu, and zinc-cobalt tailings of 2.1 million tonnes at 0.14% Co and 1.2% Zn for 4.4 million tonnes (total) of treatable tailings. The resource estimate is based on approximately half of the available tailings. Operations, planned to commence in 2019, will produce a mixed hydroxide precipitate (Cape Lambert Resources, 2019; IRW Press, 2019).

- The Kakanda tailings project with NI 43-101 measured and indicated resources of 18.5 million tonnes and an average grade of 1.25% Cu and 0.15% Co (Lutandula & Maloba, 2013; World Bank, 2008). Preliminary exploration on this project was carried out by Simberi Mining Corporation and Greenock Resources, but it was subsequently acquired by BeWhere Holdings Inc. (Greenock Resources, 2015; Simberi Mining Corporation, 2008). Boss Mining, part of ERG Africa (ERGA), which also operates in Kakanda, recovers cobalt from historic tailings within its licence area. Cobalt concentrate is refined in Zambia (ERGA Chambishi Metals) to produce cobalt metal (ERGA, 2019).

- The Kambove tailings ('geological resources' of 36 million tonnes at 0.89% Cu and 0.19% Co) and the Shituru and Panda tailings (geological resource of 13 million tonnes at 1.50% Cu and 0.23% Co) (Lutandula & Maloba, 2013; World Bank, 2008).

- The Metalkol Roan Tailings Reclamation project (RTR), located near Kolwezi, operated by ERGA, aims to start production in 2019. It comprises a hydrometallurgical facility, which will reprocess old tailings from mining carried out in the 1950s (ERGA, 2019). It will recover cobalt and copper from tailings previously deposited in the Kingamyambo tailings dam and the Musonoi River Valley. The total reserve (proven JORC-compliant) of the two tailings is estimated at 112.8 million tonnes with an average grade of 1.49% Cu and 0.32% Co (ERGA, 2019; Pyror & Lunt, 2003). The RTR project initial annual production target is 14 000 tonnes of cobalt and 77 000 tonnes of copper. The full capacity of the plant is set at 120 000 tonnes per annum copper and 24 000 tonnes per annum cobalt (ERGA, 2019).

- The Kitwe Cobalt-Copper tailings project in Zambia, close to the border with the DRC, is estimated to contain 6.6 million tonnes of tailings. Samples of the tailings reported up to 0.43% Co and 0.93% Cu (Cape Lambert Resources, 2017, 2019).

- The Nkana slag dump at Chambishi in Zambia is estimated at 20 million tonnes with an average cobalt content of 0.76%, although there is considerable variation in grade. Mintek developed a process for recovering cobalt from slags, which was implemented at Chambishi in 1998. This involved the installation of a DC arc furnace for processing the slags. However, ERGA, the owner of Chambishi Metals, currently operates hydrometallurgical processes for the recovery of copper and cobalt. These processes, however, are not economically viable for the production of cobalt from slag with a low cobalt content (Jones et al., 2002; Roberts & Gunn, 2014; Zhai et al., 2011).

Other projects aiming to recover cobalt from tailings and slags from both copper-cobalt and nickel-cobalt operations are being developed elsewhere. For example, QNI Resources in Australia announced that they will rework historic tailings from their nickel laterite mine deposited over the past 40 years, which have significant quantities of contained cobalt (more than 69 000 tonnes) (Creagh, 2018). Canada Cobalt has launched the Castle mine tailings initiative that aims to reprocess historic tailings to extract silver, gold and cobalt by producing a concentrate with a grade of 0.20% Co (Canada Cobalt Works, 2019). Research projects that focus on the development of recovery methods to extract cobalt from nickel tailings are also mentioned in the literature (Coto et al., 2008; Littlejohn & Vaughan, 2013; Marrero et al., 2015).

Supply from scrap

Cobalt is found in both new and old scrap. New scrap is produced from processing and manufacturing, for example, during the processes of shaping, cutting and moulding products. Old scrap is produced from end-of-life (EOL) products, such as spent lithium-ion batteries (LIBs), used turbine blades and other used parts from jet engines, used cemented carbide cutting tools, other types of spent rechargeable batteries, magnets, spent catalysts and others. In certain applications, for example in pigments, glass and paint, the cobalt is dissipated in use and cannot be recovered.

Rapidly growing markets, such as electric vehicles, will require increasing quantities of cobalt. Supply will not depend solely on new mining projects. Projections of the future stock of EOL batteries from electric vehicles (EV) in Europe suggest that approximately 1.2 million batteries will reach their EOL by 2030. This is expected to increase further to 2.6 million and 5.4 million by 2035 and 2040, respectively (Church & Wuennenberg, 2019; Drabik & Rizos, 2018). Spent LIBs will vary in their metal contents but will include cobalt (5–33%), lithium (5–7%), manganese (15–20%) and nickel (0.02–0.3%) amongst others. If these metals are recovered at EOL they can provide input feed to the battery market or other end use sectors (Choubey et al., 2017). Secondary resources, such as scrap and spent LIBs from electric vehicles, are likely, therefore, to make an important contribution to material supply. Furthermore, dealing with them in a sustainable manner will be crucial for environmental protection.

Recycling

Successful recycling of cobalt is influenced by many parameters including the particular recycling process used, the cobalt content of the EOL product, the collection rates of EOL products and the cobalt price. Cobalt alloy scrap and spent rechargeable batteries are the two most important EOL streams that are currently recycled.

A variety of recycling routes exist to treat different waste streams. For example, alloy scrap produced during casting and manufacturing (new scrap) can be re-melted directly without treatment or follow different recycling processes within the same manufacturing plant. Recycling of EOL cobalt alloys often takes place in existing smelter and refining facilities together with primary cobalt. The benefits of using conventional large smelters for recycling cobalt alloy scrap are the ability to process large quantities of material and to recover other metals that co-exist with cobalt in the alloys. The recycling of cobalt-containing alloy scrap in conventional electric arc smelters has been ongoing for many years (Ferron, 2013). The scrap is added to the process feed at the same point as the sulfide concentrate.

Cobalt and nickel scrap is available in various forms (large pieces, grindings, turnings) and from a variety of materials and EOL products (superalloys, nickel-cobalt alloys, lithium-ion batteries, catalysts). It is important that the feed of cobalt-containing scrap does not introduce harmful impurities to the smelter. In order to achieve this, the material is sourced according to specific standards. Some cobalt is lost during smelting as it is easily oxidised. However, a proportion of this is recovered during the slag cleaning process (Ferron, 2013).

Cobalt alloy scrap is commonly recycled in secondary smelters, which re-melt alloy scrap of many different forms and compositions. Assaying and sorting waste is very important for secondary smelters. The process involves melting the scrap in an electric arc or induction furnace under non-oxidising or reducing conditions followed by refining and casting (Ferron, 2013). The efficiency of recovery of cobalt from secondary smelters is estimated at 60–85 per cent (Crundwell et al., 2011).

Hydrometallurgy is also used to recycle cobalt scrap. These are typically smaller operations recovering cobalt, nickel and other metals (e.g. tantalum, tungsten and rhenium) that are often lost in a smelter. A simplified process involves leaching the alloy scrap in sulphuric acid or hydrochloric acid, solid–liquid separation and washing, purification and extraction of cobalt by solvent extraction (Crundwell et al., 2011; Ferron, 2013).

Spent cemented carbides are commonly recycled using the zinc method. This involves dissolving the cobalt in the cemented carbide in molten zinc, followed by melt distillation, which removes the zinc and leaves the cobalt in a spongy cake. The cobalt metal powder is recovered after crushing and screening of the cake to separate it from the other hard carbide metals (Ferron, 2013; Malyshev et al., 2015).

Recycling of spent catalysts may take place in conventional smelters, in a similar manner to cobalt alloy scrap. Depending on their composition, spent catalysts with high content of precious metals, are recycled in precious metal refineries (e.g. by Umicore at Hoboken in Belgium) (Ferron, 2013; Umicore, 2019). Certain petroleum catalysts can be recycled by regeneration. In this process, the carbon and sulphur deposited on the catalyst inhibits the catalytic activity. By burning it off, the catalyst recovers 70 to 80 per cent of its original capacity. Other hydrometallurgical methods are also available (Ferron, 2013; Gladieux Metals Recycling, 2019).

The recycling of rechargeable batteries is complex due to the wide range of battery types (lithium-ion, nickel-cadmium and nickel-metal hydride) and their different chemistries and forms. There is extensive literature dealing with this topic (Choubey et al., 2017; Gaines, 2018; Huang et al., 2018; Mayyas et al., 2019; Sattar et al., 2019; Tkaczyk et al., 2018; Zhang et al., 2018).

In general recycling of batteries involves mechanical recovery, pyrometallurgy, hydrometallurgy and combinations of these processes (Lebedeva et al., 2016; Mayyas et al., 2019; Tkaczyk et al., 2018). Mechanical processes include breaking the battery cells apart to concentrate the metals and safe removal of the electrolyte. Cryogenic processes, such as employed by Retriev, may also find use in mechanical recycling of LIBs (Retriev Technoligies, 2019). One issue with direct recycling (mechanical recovery) that does not involve pyrometallurgy or hydrometallurgy is that the quality of the cathode materials retrieved may not conform to manufacturers' specifications and they may end up being downcycled (Mayyas et al., 2019).

Pyrometallurgy has been successfully used for LIB recycling for many years. Lithium-ion cells are processed in a smelter without mechanical pre-treatment and metals such as cobalt, nickel, copper, iron are recovered as a metal alloy. The lithium, aluminium and manganese end up in the slag and are not recovered (Lebedeva et al., 2016; Mayyas et al., 2018). Pyrometallurgy is flexible as it can accommodate various LIB chemistries and input feeds, and can handle large volumes of material. However, high energy consumption, the need for gas treatment to avoid harmful emissions to the air and the common requirement for additional refining steps are problematic and have led to the development of alternative recycling routes (Gaines & Spangenberger, 2017; Mayyas et al., 2019).

Hydrometallurgical processes require mechanical pre-treatment to remove organic compounds and graphite, which adversely affect the leaching and solid–liquid separation. The cathode metals, including cobalt, are recovered using acid leaching followed by precipitation for the recovery of lithium (Gaines & Spangenberger, 2017).

A combination of methods is commonly used to effect metal recycling. For example, the Umicore plant uses pyrometallurgy to recover an alloy consisting of cobalt, nickel and copper from spent lithium-ion and NiMH batteries suitable for further processing by downstream hydrometallurgical steps (Umicore, 2019). The Recupyl process uses a combination of mechanical treatment and hydrometallurgy to extract the metals from spent LIBs (Recupyl, 2019). Sumitomo Metal Mining Co., Ltd. (SMM) has established a process that combines pyrometallurgy (Toyo Smelter & Refinery) and hydrometallurgy (Niihama Nickel Refinery) for the recovery of metals that are then used to manufacture new batteries (Sumitomo Metal Mining, 2017).

Europe seeks to establish a world-leading industry for managing EOL batteries. This is driven by the high import reliance on cobalt and other battery raw materials, the presence of a large automotive sector moving rapidly towards electrification, a legislative framework promoting the circular economy and the presence of substantial battery recycling infrastructure, (Alves Dias et al., 2018; European Commission, 2019; Lebedeva et al., 2016). Large scale recycling of EV batteries is expected to happen in Europe only after 2025, as sufficient stock from EV batteries will not be available before then. It is estimated that by 2030 recycled cobalt from spent EV batteries could supply approximately 10 per cent of the cobalt consumed in the EU EV sector (Alves Dias et al., 2018). Recycling of spent batteries with the recovery of cobalt is taking place in Belgium (Umicore), Germany (Accurec Recycling GmbH), France (Valdi), Switzerland (Batrec Industrie AG), Norway (Glencore–Nikkelverk), Finland (AkkuSer Oy) and potentially elsewhere (Lebedeva et al., 2016; Schüler et al., 2018).

In order to model the supply of cobalt from recycling of EOL products, a good understanding of the supply chain, consumer behaviour, the lifetimes of products and the estimated percentage recycled at EOL is required (Harper et al., 2011). The assessment of the level of recycling is carried out using a variety of different indicators. The United Nations Environment Programme (UNEP) estimated the EOL recycling rate for cobalt as 68 per cent (UNEP, 2011), meaning that for every 100 tonnes of cobalt contained in EOL products 68 tonnes is recycled and available for reuse (i.e. 'old scrap'). This does not include new scrap. The same report also estimated that for cobalt the recycled content of fabricated metal is 32 per cent (UNEP, 2011), i.e. the total scrap, both 'old scrap' and 'new scrap', contained within the total quantity of cobalt metal used by manufacturers. Other literature sources report a range of recycling rates for different EOL cobalt-bearing products (Harper et al., 2011; Huang et al., 2018; Tkaczyk et al., 2018).

Recycling can play an important role in the cobalt supply, but there are associated challenges and barriers to overcome both in the short and long-term. Raw material price fluctuation influences both primary and secondary materials. Cobalt is not the only metal contained within scrap, and the economics of recycling will be affected by the presence or absence of other metals of interest and the prices of those metals. Inefficiencies in the collection of EOL products result in low collection rates, which in turn adversely affect the viability of the metal recycling sector. Hibernation of products[1], such as consumer electronics, lack of adequate consumer engagement and safety issues associated with waste management practices can also influence secondary supply. Uncertainties in material compositions, especially for spent LIBs in the longer term, will affect the recycling of cobalt (Church & Wuennenberg, 2019; Mayyas et al., 2019). As with primary production, for recycling to be economically viable, economies of scale are important to maximise the economic and recovery benefits (Wang et al., 2014).

World trade

Cobalt is traded globally in a variety of forms including ores and concentrates, mattes and intermediates and refined products. The refined products are tailored to end use market requirements and are traded as oxide, hydroxide, powder, metal, sulphate, chloride, nitrate, acetate, carbonate and numerous other compounds of varying cobalt content. Trade statistics do not provide data for all the different cobalt products. Several forms of cobalt are commonly grouped under a single trade code.

In this analysis, trade data following the Harmonised System of trade codes were used:

- Cobalt ores and concentrates (HS 2605)
- Cobalt oxides and hydroxides (HS 2822)
- Cobalt; mattes and other intermediate products of cobalt metallurgy, cobalt and articles thereof, including waste and scrap (HS 8105)

No adjustments have been made for cobalt content in this analysis. Instead, the gross weight of the different traded forms is compared and discussed. The cobalt content can vary significantly for different traded forms. Adjusting for cobalt content is not straightforward, especially for the 'mattes and intermediates, unwrought cobalt, waste and scrap' (HS 8105) code, which includes several different cobalt-bearing materials with cobalt contents ranging from 20% to 100% Co.

Data for global net imports[2] of cobalt (Figure 19) show that 'mattes and intermediates, unwrought cobalt, waste and scrap' (HS 8105) and 'ores and concentrates' (HS 2605) are the major traded forms. Global net imports of ores and concentrates have halved since 2008. At the same time, there has been an upward trend in net imports of 'mattes and intermediates, unwrought cobalt, waste and scrap', especially since 2012. This is consistent with the recent increases in cobalt mine and refined production (Figure 15 and Figure 16).

Net exports from the main exporting countries in 2017 are shown in Figure 20 and Figure 21. The DRC is the world's largest net exporter of all three cobalt trade flows analysed. Net exports from DRC are nearly two orders of magnitude greater for 'ores and concentrates' (HS 2650) than net exports of ores and concentrates from all other countries. Net exports of 'oxides and hydroxides' from DRC are six times greater than from China, which is the second largest net exporter of 'oxides and hydroxides' (HS 2822). Net exports of HS 8105 from DRC are nearly 35 times greater than from Finland, the second largest exporter of these materials. This is not surprising considering that the DRC is the largest mine producer globally. However, there is considerable uncertainty regarding

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[1] Products in hibernation remain in the 'in-use' stage although they are no longer in use. They do not end up in the EOL stock and therefore valuable materials are not recovered.

[2] Net imports are calculated by subtracting the quantity of total exports in a single year from the total imports in the same year for a traded form of cobalt.

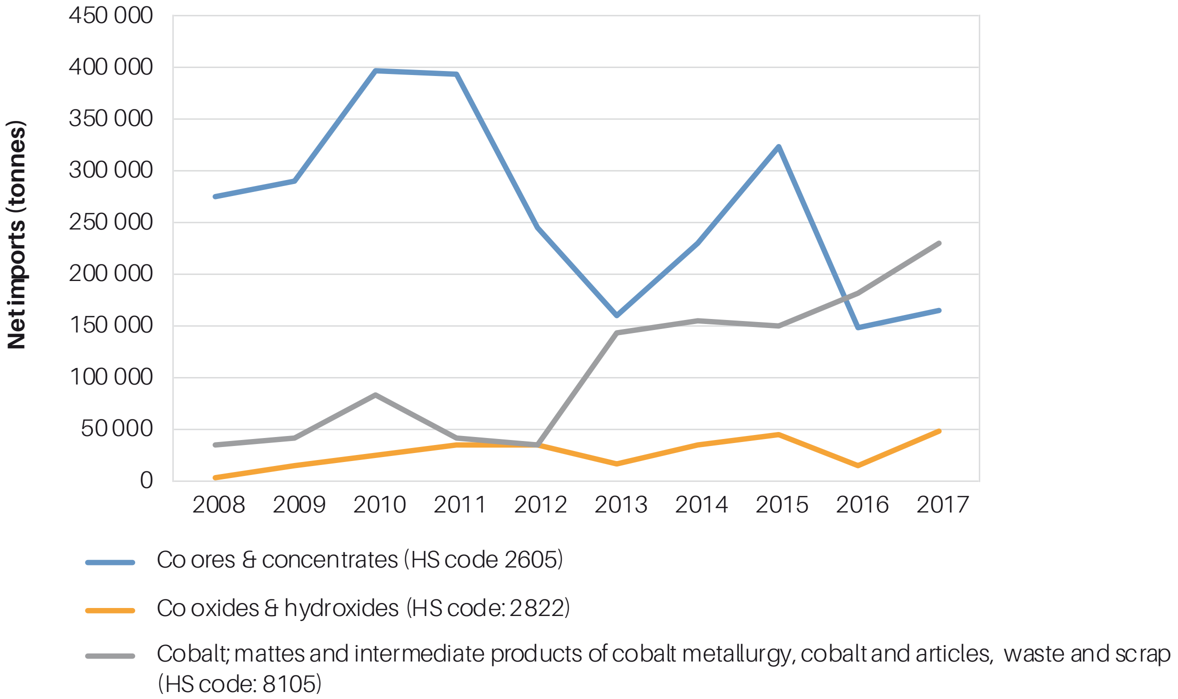

Figure 19 Trends in global net imports of cobalt between 2008 and 2017 (Data source: United Nations (2019)).

some of these data. For example, the material reported as 'oxides and hyrdroxides' for the DRC is not necessarily the same material that China exports. 'Oxides and hydroxides' produced in DRC are of an impure form, which are further refined in China and elsewhere. Equally, the trade flow for 'mattes and intermediates, unwrought cobalt, waste and scrap' (HS 8105) from the DRC represents intermediate forms of cobalt rather than unwrought metal, as cobalt refining takes place outside DRC.

Net exports[3] from the DRC mirror the global net import trends. Between 2008–2017 global exports of 'ores and concentrates' (HS 2605) have fallen, while exports of 'mattes and intermediates, unwrought cobalt, waste and scrap' (HS 8105) have increased. This is likely to be due to the installation of additional beneficiation and processing capacity in the DRC, but may also result from miscoding of the traded forms of material.

The Harmonised System trade code for 'mattes and intermediates, unwrought cobalt, waste and scrap' (HS 8105) does not differentiate between cobalt compounds. As a result, it is not possible to undertake an analysis of specific traded cobalt compounds from individual countries such as DRC. It is possible that the net exports shown in Figure 20 and Figure 21 for the different countries represent different compounds, and consequently different stages in the cobalt supply chain. Other important net exporters, such as China and Finland, have major refining capacity in country to produce compounds containing higher levels of cobalt. This downstream refining capacity does not exist yet in the DRC.

Major global net imports of cobalt to individual countries are illustrated in Figure 22 and Figure 23. The importance of the trade between the DRC and China is apparent in both figures. China is the largest net importer of 'ores and concentrates' (HS 2650) and of 'mattes and intermediates,

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[3] Net exports are calculated by subtracting the quantity of total imports in a single year from the total exports in the same year for a traded form of cobalt.

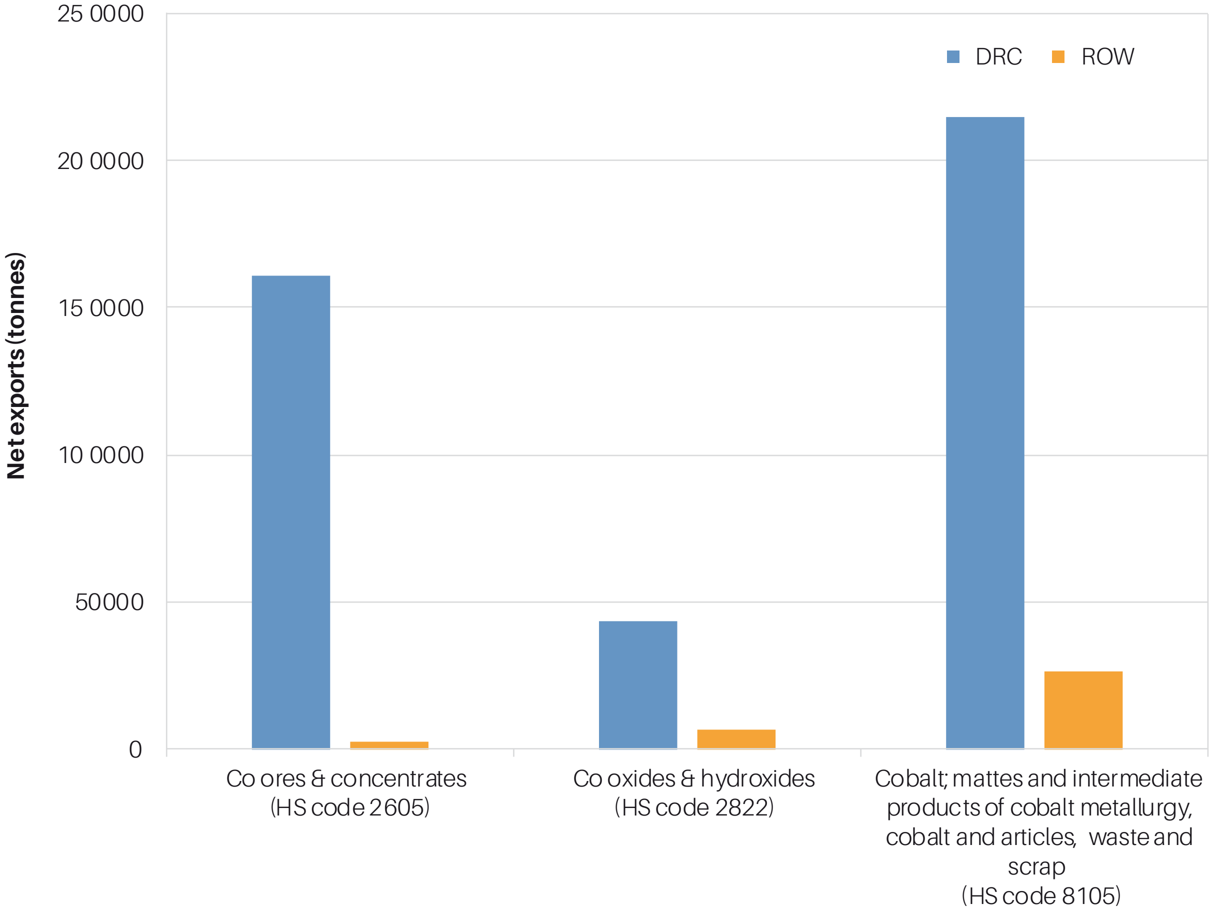

Figure 20 Net exports of cobalt materials from the DRC and the rest of the world (ROW) in 2017. Data source: United Nations (2019)).

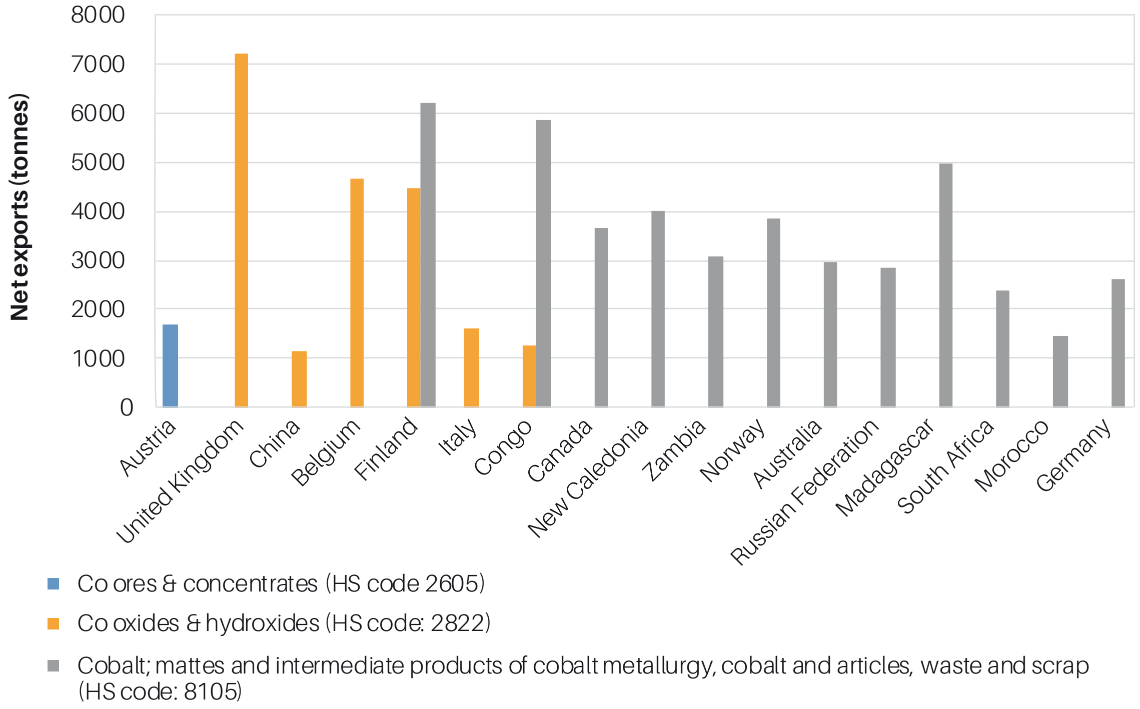

Figure 21 Net exports of cobalt materials from the major exporting countries, other than the DRC, in 2017. (Data source: United Nations (2019)).

unwrought cobalt, waste and scrap' (HS 81050). The latter are sourced from several countries to provide sufficient stock for China's refining and manufacturing sectors. Major net importers of 'oxides and hydroxides' (HS 2822) are Zambia, the Republic of Korea and Switzerland. Zambia imports 'oxides and hydroxides' from the DRC and exports some of them to Switzerland and South Africa. The Republic of Korea imports oxides and hydroxides (HS 2822) from China. All other net import flows are much smaller and are mostly between major refiners and their supply sources.

The import reliance on the DRC is evident in all cases. As China is the major importer of upstream cobalt materials (particularly ores and concentrates, mattes and intermediates), it is evident that the downstream supply chain (i.e. products and components containing cobalt) is highly reliant on China. For example, according to UN trade statistics, China is the largest net exporter of lithium-ion batteries (United Nations, 2019).

Europe is a net importer of 'mattes and intermediates, unwrought cobalt, waste and scrap' (HS 8105). According to the Cobalt Institute (2019f), EU Member States' imports account for about 14 600 tonnes of cobalt metal, 600 tonnes of cobalt salts (e.g. carbonate, dichloride, sulphate), 9700 tonnes of inorganic cobalt compounds (e.g. cobalt oxide, hydroxide) and 3500 tonnes of carboxylates. In addition, the EU Member States have substantial manufacturing capacity in place for these cobalt compounds (Cobalt Institute, 2019f). Overall, it is estimated that 70 per cent of the cobalt compounds manufactured and imported into the EU are used by downstream industry (e.g. the automotive and aerospace sectors) within the EU, with the remaining 30 per cent exported. The annual quantity of cobalt compounds exported from the EU is estimated at 30100 tonnes (Cobalt Institute, 2019f).

Normally, only formal and legal operations are included in trade statistics. There is, therefore, an element of uncertainty about the trade of cobalt ores and concentrates produced by informal operations. Various sources suggest that cobalt ore produced from informal mining operations is sold to wholesale traders and cooperatives, who, in turn, sell on to processing companies for the production of cobalt concentrates (Amnesty International, 2016; DERA, 2018; Faber et al., 2017). It is likely, therefore, that the majority of the output from informal mining is captured by international trade statistics as the export from these processing companies is recorded. However, some quantities may enter illegal trade routes and be excluded from global trade data. At present, it is not possible to quantify informal trade in cobalt compounds.

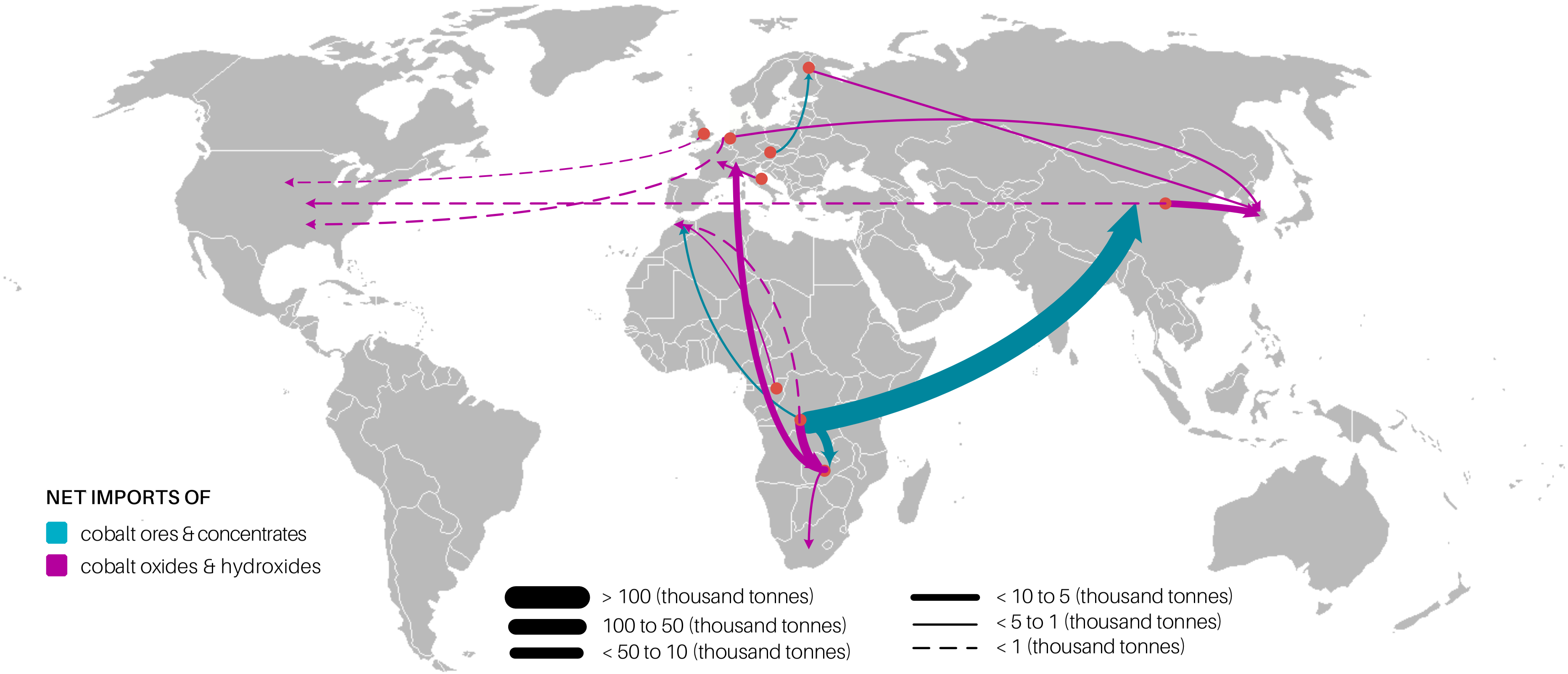

Figure 22 Global major net import flows of cobalt ores and concentrates (HS 2605) and cobalt oxides and hydroxides (HS 2822) in 2017 (Data source: United Nations (2019)). Some trade flows can not be shown because of the limited availability of data.

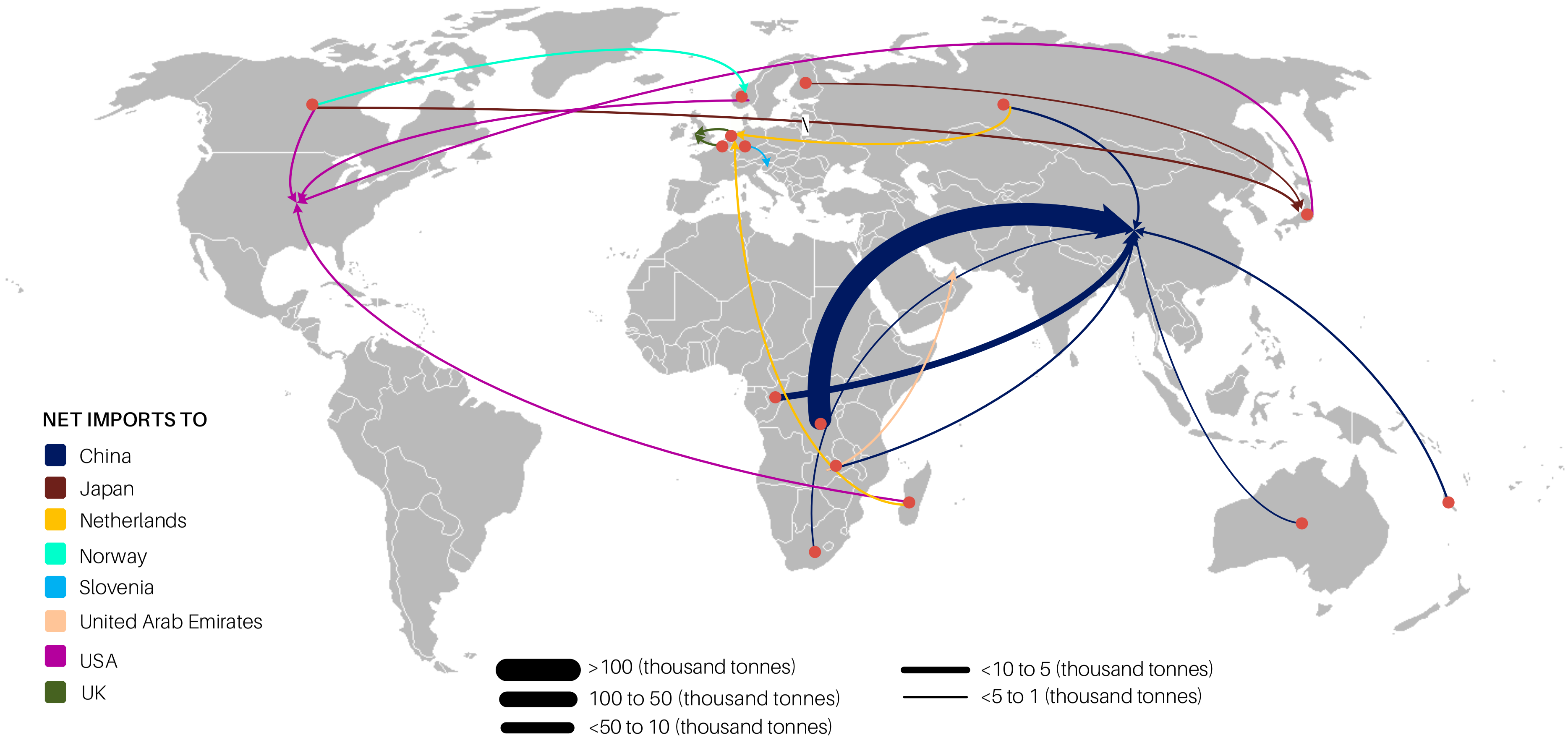

Figure 23 Global major net import flows of cobalt; mattes and intermediate products of cobalt metallurgy, unwrought cobalt, waste and scrap (HS 8105) in 2017 (Data source: United Nations (2019)). Some trade flows can not be shown because of the limited availability of data.

Prices

For many years, cobalt prices were only available from the London Metal Bulletin free-market quotation and this is still commonly used, although Metal Bulletin is now owned by Fastmarkets. Prices are available on subscription for two main grades of metal 99.80 per cent (high grade) and 99.30 per cent (low grade) (Fastmarkets, 2019). In addition Fastmarkets provides prices for cobalt hydroxide, cobalt sulfate and cobalt tetroxide. Prices for cobalt metal with a minimum of 99.80 per cent purity are also available from the London Metal Exchange (LME), which began trading in cobalt in February 2010 (LME, 2019a, b).

Cobalt price movements between 1970 and 2010 have been reviewed by Shedd (2013). The price has varied in response to general global economic conditions, supply and demand fundamentals and several other factors of relatively short duration. Political and economic instability and civil unrest in the DRC have long influenced global cobalt supply and prices. Other factors that have been important at various times include sales from the United States' government stockpile and increased supply from Russia following the break-up of the Soviet Union. More recently, a significant increase in cobalt demand for use in batteries, particularly from China, has led to concerns about the adequacy of global supply which increase prices.

During 2003, cobalt prices increased sharply in response to reduced production and concerns over tightness in global supply. During the commodity boom that followed, prices continued to rise peaking in early 2008 close to US$50 per pound. With the ensuing global financial crisis and economic downturn, demand fell and prices slumped to below US$13 per pound in December 2008. Despite a short-lived upturn during 2009, attributed to growing battery demand and concerns about supply from Canada and Zambia, the cobalt price followed a general downward trend between 2010 and late 2016 (Figure 24). Thereafter the price rose sharply to a near decade high in March 2018, with an average price in the second quarter of nearly US$43 per pound. The fundamental reasons for this spectacular increase were strong demand from consumers in China

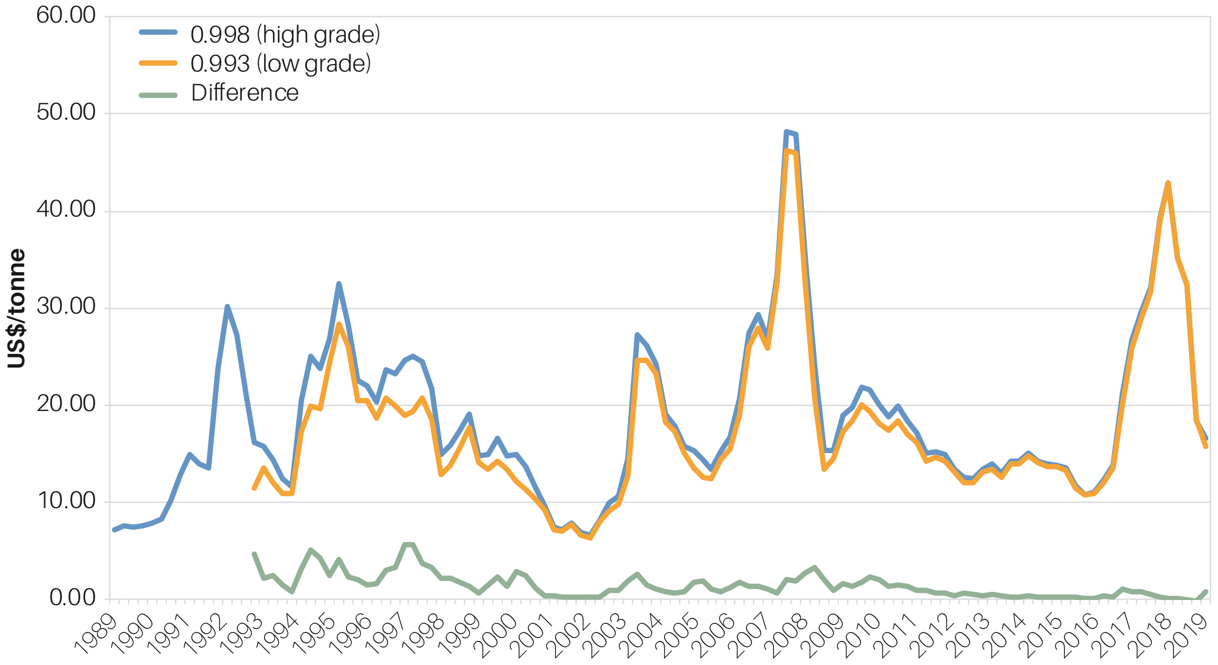

Figure 24 London Metal Bulletin cobalt price 1989 to second quarter 2019 (Data source: Cobalt Institute).

for rechargeable batteries, together with concerns about mine production from the DRC and the availability of cobalt metal from refineries in China. After this peak, the price fell back by about 60 per cent in the following year. The main reasons for this were increased supply from mines in the DRC, notably Katanga and Kamoto, together with reduced demand for EV batteries in China. Cuts to subsidies on EVs in China, announced in March 2019, with all subsidies to be phased out by 2021, have further impacted on demand (Reuters, 2019a).

Substitution

Substitution is commonly employed by industry to improve product performance, reduce costs and address issues with material supply. Cobalt has numerous applications, although in some of these substitution is not an option, for example when cobalt is used in medical diagnosis (e.g. absorption of vitamin B12) and in the pharmaceutical sector.

Rechargeable batteries are the largest cobalt-consuming market at present. However, there is a range of battery technologies available, with different configurations and metal requirements, and these could be considered as potential product-to-product substitutes. The lithium-ion battery (LIB), currently the most popular battery type, uses cobalt in the cathode. The most important types of LIB are the lithium-cobalt-oxide (LCO), the lithium-nickel-cobalt-aluminium-oxide (NCA) and the lithium-nickel-manganese-cobalt oxide (NMC) (Gunn & Petavratzi, 2018). The cobalt content of these batteries varies considerably. For example, the cathode of the LCO type used in portable electronics consists primarily of cobalt, whilst the NMC111 class that is widely used in electric vehicles, comprises equal quantities of nickel, manganese and cobalt. However, there is a growing trend to substitute high cobalt LIBs with low cobalt, high nickel types (e.g. NMC 532, NMC 622, NMC 811) to reduce their cost (Battery University, 2019a). This shift does not represent complete removal of cobalt from NMC type LIBs. Other battery technologies exist, that are entirely cobalt-free, for example the lithium iron phosphate (LFP) type and the lithium manganese oxide (LMO) type. Each has some associated performance penalty that restricts their use to particular applications. Several other battery systems, that may become widely used in the future, are the focus of considerable global research and development. These include solid state LIBs, and zinc-air (Zn-air), lithium sulphur, lithium-air and lithium metal types (Battery University, 2019b).

Cobalt-based superalloys, used primarily in gas turbines, have been the subject of considerable research over many years. The key objective has been to reduce their weight, whilst retaining their ability to operate at high temperature and pressure. Alternative materials include fibre-reinforced metal matrix composites (MMC), ceramic-ceramic and carbon-carbon composites, titanium aluminides, nickel-based single crystal alloys and iron-based superalloys (Cobalt Institute, 2019a). However, substitution of superalloys in the aerospace industry is a lengthy process. It requires many years of research and testing to prove the benefits in material performance and economics, and to acquire regulatory approval.

Neodymium-iron-boron magnets are increasingly used in place of cobalt-rich permanent magnets, such as the samarium-cobalt and aluminium-nickel-cobalt types. The neodymium-iron-boron magnet provides much improved performance and requires only a very small quantity (if any) of cobalt in the coating layer (Alves Dias et al., 2018; Cobalt Institute, 2019g). However, the cobalt-rich magnets are still used in many applications.

Hardfacing materials use cobalt in cemented carbides as a binder. In diamond tools, cobalt can be substituted by cobalt-iron-copper or iron-copper. Other potential substitutes that have been considered include nickel, nickel-aluminium, iron and ruthenium. However, these involve some loss of performance for these hard materials' applications. In addition, the cost of some of the substitutes, for example ruthenium, would inhibit substitution (Espinoza et al., 2015; European Commission, 2017b).

There are no substitutes for the use of cobalt in pigments with equivalent colouring, stability and solubility results in ceramics, glass and other products. For example, complex dyes of cobalt have a high light-fastness, which none of the potential substitutes can achieve often resulting in colour fading (Alves Dias et al., 2018; Cobalt Institute, 2019b; European Commission, 2017b).

Potential substitutes for cobalt in catalysts include ruthenium, molybdenum, nickel and tungsten, but they all come with loss of performance making cobalt the metal of choice in such applications (Cobalt Institute, 2019c; Espinoza et al., 2015).

Responsible sourcing

There is growing public concern that materials such as cobalt are sourced in a responsible manner and that their supply chains are ethical, transparent and compliant with international standards. The broad topic of responsible sourcing of minerals involves consideration of traceability, elimination of human rights abuses and improving mineral governance. New technologies, such as blockchain, have also been introduced and their importance in ensuring transparency and auditability is expected to grow.

Traceability is defined as 'the ability to identify and trace the history, distribution, location and application of products, parts and materials to ensure the reliability of sustainability claims' (UN Global Compact, 2014). The importance of traceability for sustainability objectives, together with a summary of the drivers and benefits to companies related to traceability, are outlined in a UN publication from 2014 (UN Global Compact, 2014). Businesses can gain from enhanced traceability by reducing risk, improving operational efficiencies, securing supplies and deriving reputational benefits. At the same time, better traceability will also help meet stakeholder demands for more product information.

In 2008 a report by a United Nations Group of Experts challenged the extractives industry in the DRC to act against the non-governmental armed groups and to establish transparent due diligence processes for the responsible supply of minerals from conflict zones (Stearns et al., 2008). In 2011, the OECD published a set of guidelines on responsible supply chain management from conflict-affected areas that was endorsed by governments, NGOs and industry (OECD, 2011). The objective of the Guidance is to help companies respect human rights and avoid contributing to conflict through mineral sourcing practices. It aims to clarify what should be expected of responsible supply chain management of minerals from conflict-affected and high-risk areas (OECD, 2011).

The latest edition of the OECD Guidance emphasises that it is a framework for due diligence as a basis for responsible supply chain management of all minerals, not just TTTG (tin, tungsten, tantalum and gold) (OECD, 2016). The Guidance clarifies how companies can identify and manage risks throughout the mineral supply chain. It also seeks to promote responsible private sector engagement in post-conflict fragile states by helping companies respect human rights, observe international humanitarian law, avoid contributing to conflict and cultivate transparent mineral supply chains and sustainable corporate engagement in the minerals sector. One of the main areas of focus is to improve opportunities for artisanal and small scale mining (ASM)(see also section on supply from artisanal mining), through building secure, transparent and verifiable supply chains and to ensure that the benefits accrue to legitimate ASM communities. The OECD Guidance has effectively become the international standard used by governments and other agencies. It is now referenced and used in binding regulations on responsible mineral supply chains in China, USA and the EU (CCCMC, 2015; European Commission, 2017a; Securities & Commission, 2017). It is also part of the legal framework in several African countries, including the DRC, Burundi and Rwanda.

In 2016 Amnesty International identified numerous instances of unregulated, unauthorised and unsafe mining of cobalt in the DRC, commonly involving the use of child labour, which raised concerns about its responsible sourcing (Amnesty International, 2016). Amnesty called for regulation to ensure transparency across the supply chain of cobalt and other minerals, requiring companies to disclose their due diligence practices and to take action to remediate the harm suffered by people at any point during their operations. Amnesty subsequently reported on the policies and practices of 29 companies in identifying, preventing, addressing and accounting for human rights abuses in their cobalt supply chains (Amnesty International, 2017). It was concluded that none of the companies investigated was carrying out human rights due diligence on their cobalt supply chains in line with international standards. It was also pointed out that there is currently no law anywhere in the world that requires transparency of human rights risks and abuses in cobalt extraction and trading. However, it should be noted that some large 'original equipment manufacturers' (OEMs) have begun to take human rights due diligence very seriously. For example, Sony and Apple now track cobalt throughout their supply chains, back as far as the original source (Apple, 2019; Sony, 2019). In the automotive sector BMW announced that from 2020 it will buy cobalt for its next generation of electric vehicles from mines in Australia and Morocco, rather than from small-scale mines in the DRC (Investing News, 2019). Tesla has also developed a Human Rights and Conflict Minerals Policy and a Supplier Code of Conduct which confirm its commitment to only using responsibly produced materials (Tesla, 2018).

Since 2016 various industry-led programmes have started to promote the widespread adoption of the OECD Guidance in the cobalt supply chain. China has a major role to play in the implementation of due diligence as they are the largest global importer of cobalt raw materials and the largest cobalt refiner in the world. Following adoption of the Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains by the Chinese Chamber of Commerce for Metals, Minerals & Chemicals (CCCMC) in December 2015, the CCCMC and the OECD launched the Responsible Cobalt Initiative (RCI) in November 2016 (Respect, 2016).

Another programme related to responsible sourcing of minerals and metals, including cobalt, is the Responsible Minerals Initiative (RMI) which was founded in 2008 (RMI, 2019a). The mission of the RMI is to help companies make sourcing decisions that improve regulatory compliance and support responsible sourcing from conflict-affected and high-risk areas. For example, the Responsible Minerals Assurance Process (RMAP) seeks to identify smelters and refiners that produce responsibly sourced materials.

In October 2019 the LME announced its responsible sourcing requirements which are underpinned by the OECD Guidance and which require full compliance of all LME-listed brands, including products from numerous cobalt suppliers, by 2023 (LME 2019a and 2019b). Buyers of metal on the LME will be thus be assured that all brands meet a minimum level of responsible sourcing compliance.

The Cobalt Institute, with assistance from consultants RCS Global, has developed the Cobalt Industry Responsible Assessment Framework (CIRAF), which began to be implemented during 2019 (Cobalt Institute, 2019h). CIRAF is a reporting framework and management tool for the cobalt industry and its customers. RCS Global has also launched two other products aimed at providing data to underpin responsible production needs and raw material sourcing. 'Better Sourcing' is a mineral supply chain due diligence scheme working on TTTG and cobalt in Rwanda and the DRC that was established in 2014 (RCS Global, 2019). 'Better Cobalt', a pilot project in the DRC cobalt mining sector, collects data to monitor how cobalt production and trade contributes to an improvement of social and responsible practice (RCS Global, 2019).

Responsible sourcing is now generally incorporated in mineral governance initiatives. The Extractive Industries Transparency Initiative (EITI) is a global standard for the good governance of oil, gas and all mineral resources, including cobalt, and the prevention of corruption and mismanagement (OECD, 2019). The EITI complements the OECD Guidance with both providing a disclosure and governance framework for companies to ensure that transparency across the minerals supply chain reduces corruption and conflict in mineral extraction. The original focus of the EITI, launched in 2003, was on publication of revenue flows between businesses involved in mineral extraction and national governments. Since then the scope of the EITI has broadened to include disclosure requirements on environmental, social and gender issues as well as fiscal and legal matters (EITI, 2019). Nearly 60 countries have committed to implement the EITI Standard (Lujala, 2018).

A number of international multi-stakeholder platforms have been established to identify key challenges in responsible material sourcing and to determine how they can be solved. Of particular relevance to cobalt are alliances in the field of battery raw materials. The Global Battery Alliance, launched in September 2017 by the World Economic Forum, is a collaborative platform to accelerate action towards a socially responsible, environmentally sustainable and innovative battery value chain (World Economic Forum, 2019a). In October 2017 the European Commission launched the European Battery Alliance with the aim of establishing a complete battery value chain in the EU (European Battery Alliance, 2019). In accessing materials from overseas, the EC will use all appropriate trade policy instruments to ensure fair and sustainable access to raw materials and to promote socially responsible mining.

Blockchain is a technology which initially focused on financial applications, but its versatility led to it being used in other sectors, in particular in supply chain management (Nakamoto, 2008; Kouhizadeh & Sarkis, 2018). Blockchain is a secure database of records stored as 'blocks' on a network of computers. Data records, such as weight, quantity, grade, provenance information and responsible production certificates, can be uploaded at appropriate points in the supply chain. The records at each stage are validated against the previous record, thereby making any alteration difficult. These immutable blocks constitute a blockchain of linked records that can be shared with buyers and other third parties. The blockchain technology offers improved operational efficiencies, but also minimises the risk of fraud and builds confidence and consensus around responsible production standards and traceability between downstream and upstream companies. A study commissioned by the ICMM concluded that blockchain databases have significant potential to improve traceability and transparency in mineral supply chains and to incentivise responsible production (RCS Global, 2017a).

A number of programmes have been launched with the aim of increasing the use of blockchain technology in the minerals industry. For example, MINTRAX is a blockchain platform for tracking minerals along the supply chain from mine site to end-user. The system is being piloted on Cobalt Blockchain's (COBC) cobalt trading business in the DRC (Hooper, 2019). Another programme is being led by RCS Global who have launched a Responsible Sourcing Blockchain Network in partnership with major OEMs, Ford, Volkswagen, IBM, LG Chem and Huayou Cobalt (Elective, 2019; RCS Global, 2017b; Reuters, 2019b). In October 2019 the World Economic Forum announced a new programme involving seven major mines and metals companies to develop blockchain solutions to accelerate responsible sourcing of raw materials and sustainability practices (World Economic Forum, 2019b).

Focus on the United Kingdom

Cobalt occurrences

Cobalt-bearing mineralisation has been reported from several localities in the United Kingdom, although cobalt production has been recorded from only a few sites (Figure 25).

In south-west England, cobalt was recovered from nine mines from the mid-18th century to the 19th century, with a total mine production of a few hundred tonnes (Rollinson et al., 2018). The mines with known production were: Wheal Sparnon near Redruth, Pelyn Wood Mine near Lostwithiel, Tretoil Wood Mine near Lanlivet, Trugo Mine near St. Columb, Dolcoath and East Pool near Camborne, Great Dowgas and St. Austell Consols near St. Stephen, and Pengreep, near Gwennap. Wheal Sparnon had the most significant production, from a so-called cobalt lode, which was mined solely for cobalt. The ore was mainly roasted to cobalt oxides for use in the pottery industry (Jenkin, 1979; Rollinson et al., 2018). Cobalt at these mines in Cornwall was associated with lead, zinc, silver, uranium, antimony, manganese, iron, bismuth and nickel in late mineralised fractures known as cross-courses, which cut across the main copper and tin orebodies (Rollinson et al., 2018). Cobalt-rich mineralisation has also been reported in copper-lead-zinc-silver ores associated with the Wheal Lushington mines at Porthtowan about two kilometres west of St Agnes (Rollinson et al., 2018). Mineralogical studies identified abundant cobaltite and subordinate erythrite in these ores.

In Cheshire, small amounts of cobalt were recovered from copper deposits in Triassic sandstones at Alderley Edge in the 19th century and at Clive in Shropshire (Bateson et al., 1982; Warrington, 2012). In one of the mines at Alderley Edge, cobalt was concentrated in a series of north–south faults. This mine has recently been named the Cobalt Mine but there are no data on the cobalt content of the ores nor on the scale of past production (Derbyshire Caving Club, 2019). In the Lake District, ores from Scar Crag and Dale Head North were reported to have high cobalt contents (Ixer et al., 1979; Stanley & Vaughan, 1980, 1982). Cobalt extraction was attempted in the mid-19th century at Scar Crag, which was also called the 'cobalt mine', but this was never successful (Postlethwaite, 1913). Cobalt was associated with a chalcopyrite-pyrite-arsenopyrite assemblage and was incorporated in skutterudite and sulfarsenides, such as alloclasite, glaucodot and cobaltite (Ixer et al., 1979; Stanley & Vaughan, 1982). A silver-nickel-cobalt mineral association has been described from the disused lead mine at Tynebottom, Garrigill, near Alston in the North Pennine Orefield (Ixer & Stanley, 1987; Ixer et al., 1979). These ores occurred in the Brigantian (Carboniferous) Tynebottom Limestone, which rests on the Whin Sill in this area. A variety of cobalt minerals have been reported from this locality, including cobalt and nickel arsenides, sulfarsenides and sulfantimonides.

In the 18th century cobalt ores were mined on a small scale with silver at Silver Glen, near Alva, in Perthshire, Scotland. The mineralisation occurred in veins related to Permo-Carboniferous east–west trending faults within late Devonian volcanic rocks. The cobalt mainly occurred as clinosafflorite $(Co,Fe,Ni)As_2$, a rare monoclinic polymorph of safflorite (Hall et al., 1982; Moreton, 1996). Cobalt was also reported from the Hilderston mine, near Linlithgow in West Lothian, central Scotland, where it was also associated with silver and nickel. As at Silver Glen, mineralisation occurred in Carboniferous east–west trending faults, but here it was hosted by Lower Carboniferous sedimentary rocks (Stephenson et al., 1983). The Coille-bhraghad and Craignure copper mines, near Inverary in western

Scotland, are reported to have also produced nickel-bearing minerals, pyrrhotite and pentlandite, which contained trace levels of cobalt. These deposits were associated with a suite of mafic intrusions in Neoproterozoic Dalradian metasedimentary rocks (Coats et al., 1982).

In the Central Wales Orefield cobalt occurred in pentlandite and siegenite, as a component of early polymetallic vein mineralisation, which was noted for its varied mineralogy (Mason, 1997). It has been recorded at the following mines: Erglodd, Brynyrarian, Loveden, Ystrad Einion, Esgairhir, Esgairfraith and Nantycagl (National Museum Wales, 2019). In North Wales, cobalt and nickel sulfides occur in epigenetic copper ores within Carboniferous dolostone at the Great Orme Mine, near Llandudno (Ixer & Stanley, 1996). However, cobalt production in Wales was only known from Foel Hiraddug near Dyserth, located about 30 kilometres east of Llandudno. Here the cobalt occurred as asbolane, a cobalt hydroxide, associated with manganese oxides and hematite in a clay-filled fissure hosted in limestone of Carboniferous age. Mine production of cobalt ore was estimated to have been 240 tonnes between 1878 and 1880 (North, 1962).

Recent commercial exploration for precious and base metal mineralisation in the Tyrone Igneous Complex in Northern Ireland has highlighted some potential for cobalt. Quartz-sulfide veins in a quarry in the Corvanaghan-Golden Hollow area were reported to contain up to 0.13% Co, 1.27% Cu and 50.3 g/t Ag (Walkabout Resources, 2018).

Consumption

Between 1998 and 2017, the apparent consumption of cobalt in the UK varied between 1000 and 4400 tonnes (Figure 26). In 2017, the apparent consumption[4] of cobalt was 1500 tonnes. This represents about 1.2 per cent of global apparent consumption, which is estimated at 123 000 tonnes (Cobalt Institute, 2019i). In the UK, cobalt metal is used by companies making high-performance alloys for the aerospace sector and in the cemented carbide, magnet and special steel industries. Cobalt chemicals are mainly used by glass and ceramic manufacturers and, increasingly, in battery manufacture. The calculated total UK apparent consumption of cobalt did not fluctuate markedly between 2013 and 2017. However, in the three preceding years UK consumption was much higher, with consumption in 2011 three times greater than in 2017. This increase is attributed to higher unwrought metal imports in this period. Although there is no primary (mine) production of cobalt in the UK, several companies produce specialist cobalt alloys based on imported unwrought metal and scrap.

The UK is a net importer of unwrought cobalt metal and of small quantities of ores and concentrates; it is a net exporter of, wrought, cobalt oxides and small quantities of cobalt scrap. The net imports of unwrought metal have increased considerably between 2015 and 2017. Net exports of cobalt oxides have remained stable at about 1000 tonnes (Figure 27).

There are no cobalt refiners in the UK but the Vale-owned nickel refinery at Clydach in South Wales processes nickel intermediates, such as nickel oxide, which are likely to contain cobalt. However, cobalt is not recovered during the refining process. The Clydach refinery produces nickel pellets for the stainless steel industry (Vale, 2015).

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[4] Apparent consumption equals production (primary and secondary) plus imports minus exports. All the main traded forms of the metal are taken into account.

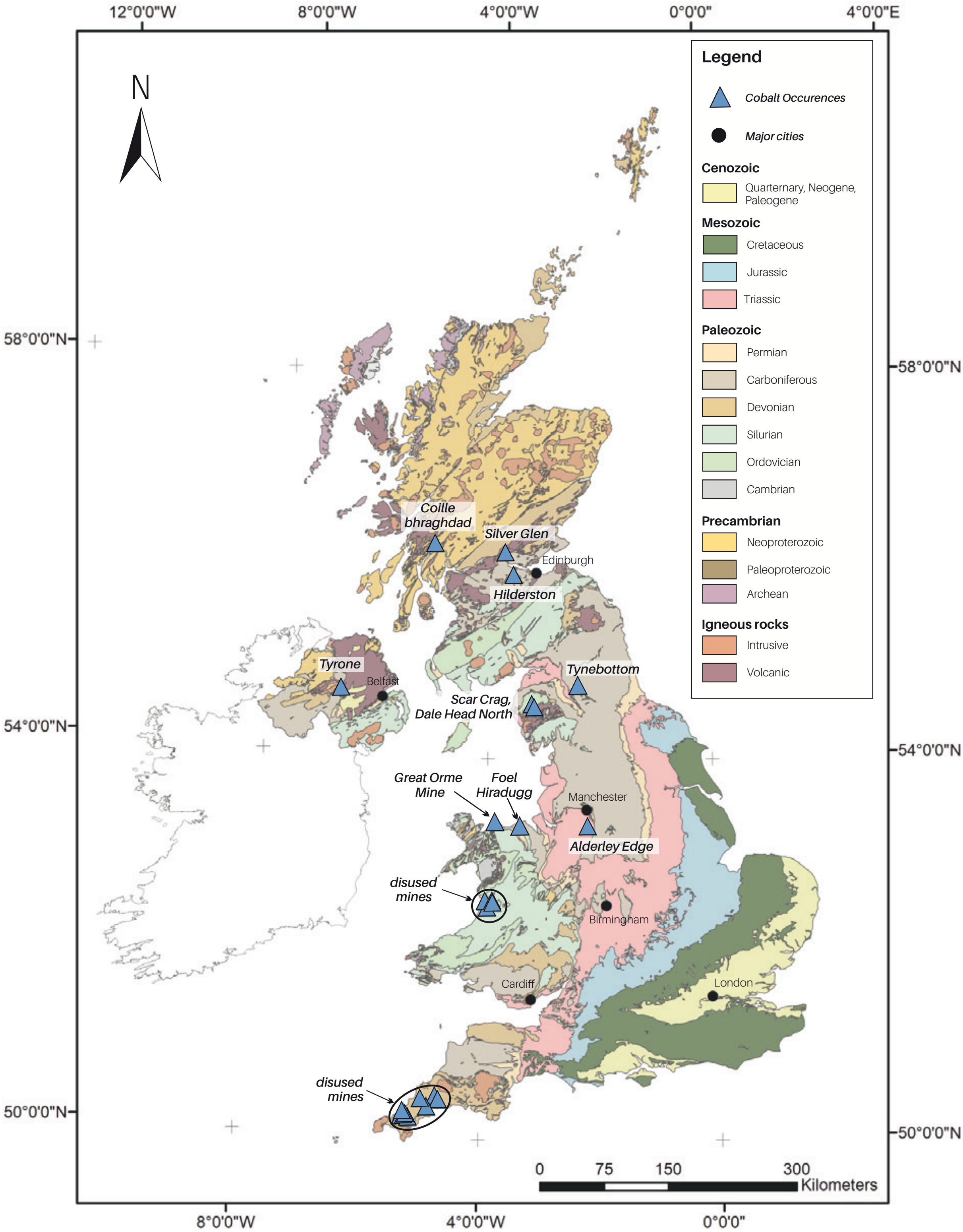

Figure 25 Location of principal cobalt occurrences in the United Kingdom.

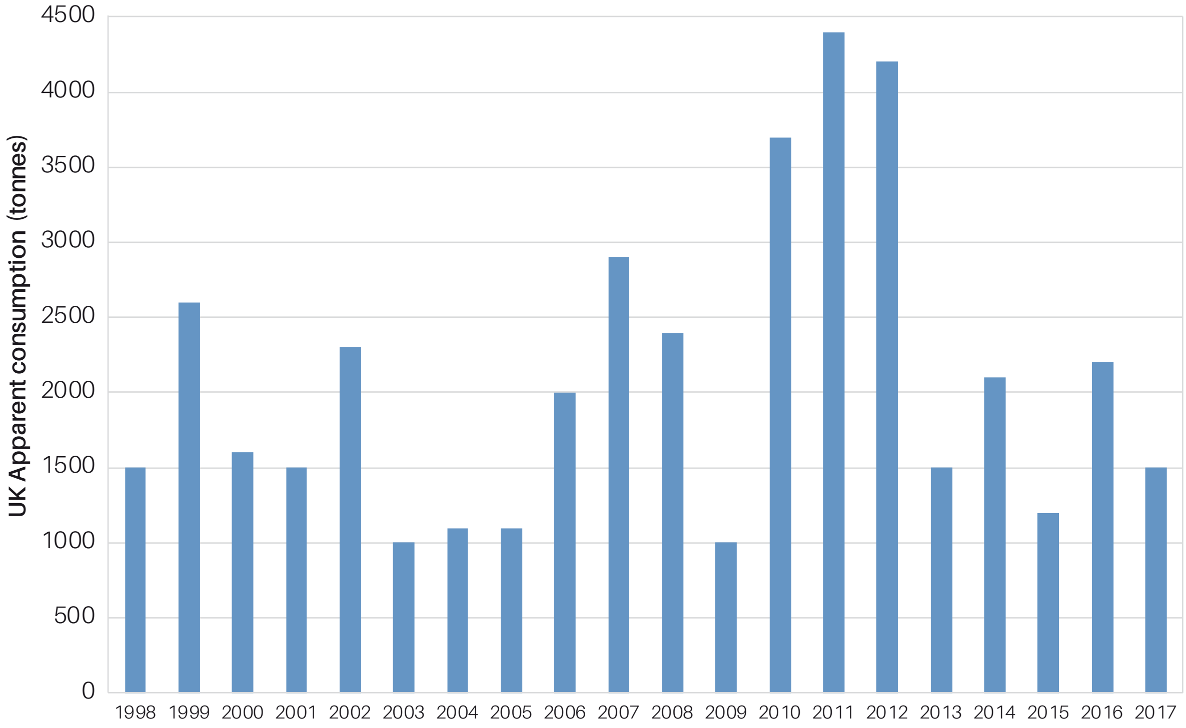

Figure 26 Cobalt apparent consumption in the UK (Data source: Bide et al. (2019)).

Figure 27 Net trade of cobalt between 2013 and 2017 (Data source: Bide et al. (2019)).

EVs and the battery supply chain in the UK

In order to achieve net zero greenhouse gas emissions by 2050 the UK has set ambitious targets for the electrification of transport, as outlined in the 'Road to Zero' strategy (Department of Transport, 2018) and the 'Net Zero - The UK's contribution to stopping global warming' document (Committee on Climate Change, 2019). The switch to ultra-low-emission vehicles (ULEVs) by 2050 will require a fast ramp up of the market share of EVs in the UK (Committee on Climate Change, 2019). The UK Government has also identified the EV and battery manufacturing industries as strategic for growing its car manufacturing sector. New EV infrastructure in the UK will require secure access to batteries and, if battery manufacture is located outside the UK, then there is the risk that the automotive EV sector will move to be close to these plants. A report from the Faraday Challenge suggests that the development of UK battery gigafactories would be essential to this sector and makes the case for the establishment over the next twenty years of four to thirteen battery production plants (Howey et al., 2019). Numerous factors would influence the establishment of a UK battery manufacturing sector. However, given that raw materials constitute over half of the cost of LIBs, secure and sustainable access to essential battery raw materials, such as cobalt, will play a prominent role in de-risking investment and boosting the development of battery manufacture in the UK.

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