

Definition, mineralogy and deposits

Definition and characteristics

Cobalt is a lustrous, greyish-silver, brittle metal. It is also very hard and can take a high polish. It retains its strength at high temperatures and it has fairly low thermal and electrical conductivities. Cobalt is also ferromagnetic, and therefore is capable of being magnetised. Other properties that are important in industrial applications are its ability to form alloys with many other metals, imparting strength at high temperatures and the ability to maintain its magnetic properties at high temperatures (up to 1121 °C, higher than any other metal). Other physical properties are summarised in Table 1.

Pure cobalt is not found in nature, but compounds are widely distributed in the Earth's crust, which overall has an average concentration of 25 parts per million (ppm). Cobalt can be found with nickel in iron meteorites and also in varying amounts in plants, animals and soil. Cobalt is vital for the health of many organisms and makes up an important part of the vitamin B₁₂, which is often given as supplements to grazing animals.

Cobalt is a transition group metal and has only one naturally occurring isotope, Co⁵⁹. There are another 22 radioisotopes of cobalt. Co⁶⁰ is one of the most commonly exploited, which has a half-life of 5.27 years and is a powerful gamma ray emitter. Cobalt has a variable oxidation state but is commonly found in +2 or +3 forms.

Mineralogy

A wide range of minerals contain cobalt although many are rare or unique to individual localities. There are approximately 30 principal cobalt-bearing minerals and over a hundred more which contain minor amounts of the metal or include cobalt as a substitute for other elements. Cobalt can substitute for transition metals in many minerals and chemical compounds and is commonly found in the place of iron and nickel as they share many similar properties.

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Symbol	Co	
Atomic number	27	
Atomic weight	58.933195	
Density at 293 K	8850	kg/m ³
Melting point	1493	°C
Boiling point	3100	°C
Crystal structure	Hexagonal close-packed	
Hardness	5.0-5.5	Moh's scale
Electrical conductivity	27.6	% (International Annealed Copper Standard)

Table 1 Selected properties of cobalt.



Figure 1 Skutterudite, a cobalt-nickel arsenide, from Morocco. BGS © NERC.

¹ Hydrothermal deposits are ones where minerals are concentrated by the movement of hot fluids.

Name	Group	Formula	Example deposits
Erythrite	Arsenate	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	Daniel Mine, Germany; Bou Azzer, Morocco.
Skutterudite	Arsenide	$(\text{Co,Ni})\text{As}_3$	Skutterud Mines, Norway; Bou Azzer, Morocco.
Cobaltite	Sulphosalt	CoAsS	Sudbury, Canada; Broken Hill, New South Wales, Australia.
Carrollite	Sulphide	$\text{Cu}(\text{Co,Ni})_2\text{S}_4$	Chambishi, Copperbelt, Zambia; Carroll County, Maryland, USA.
Linnaeite	Sulphide	$\text{Co}^{2+}\text{Co}_2^{3+}\text{S}_4$	Bou Azzer, Morocco; Noril'sk, Russia
Asbolite (Asbolane)	Oxide	$(\text{Ni,Co})_{2-x}\text{Mn}^{4+}(\text{O,OH})_4 \cdot n\text{H}_2\text{O}$	Koniambo Massif, New Caledonia.

Table 2 Common cobalt-bearing minerals found in economic deposits.

Cobalt minerals occur in concentrations high enough to support economic extraction in several diverse settings, all of which display very different examples of mineralisation. The most common groups of minerals are sulphides, sulphosalts arsenides and oxides (See Table 2). In general common rock-forming minerals do not contain significant amounts of cobalt. However, it can be found in economic concentrations in olivine, spinel and chlorite in lateritic and hydrothermal¹ deposits.

Deposits

Economic concentrations of cobalt can be found in four different geological settings, outlined in Table 3. Cobalt is almost always a by- or co-product of mining for other base metals, chiefly nickel and copper. Large quantities of cobalt also occur on the sea floor, contained within manganese nodules and cobalt-rich crusts, although these are not economically viable with current technology and economic conditions.

Deposit type	Genetic process of formation	Typical economic grades	Major examples
Sediment hosted	Diagenetic ² processes in a near-shore or saline lagoon environment convert sea water sulphates to sulphides and concentrate metallic elements sourced from sediments.	0.1 – 0.4 %	Tenke Fungurume, Democratic Republic of Congo; Mt Isa, Australia.
Hydrothermal/volcanogenic	Precipitation of minerals from hydrothermal fluids passing through the host rock.	0.1 %	Bou Azzer, Morocco; Keretti, Finland.
Magmatic ³ sulphide	An immiscible ⁴ liquid sulphide phase is concentrated in magmas. This phase preferentially collects and concentrates metallic elements such as cobalt.	0.1 %	Noril'sk, Russia; Sudbury, Ontario, Canada; Kambalda, Australia.
Laterite	Tropical weathering causes the breakdown of cobalt silicates and sulphides in ultramafic ⁵ bodies causing cobalt to become enriched in residual weathered rocks.	0.05 – 0.15%	Koniambo Massif, New Caledonia.
Manganese nodules and cobalt-rich crusts	Ferromanganese oxide concretions on the sea floor become enriched in cobalt by extraction from sea water and pore fluids from muds.	Up to 2.5 %	None currently economic.

Table 3 Summary of main cobalt deposit types.

² Diagenetic: the processes during which unconsolidated sediment becomes rock.

³ Magmatic: related to magma, molten rock and fluid originating deep within or below the Earth's crust.

⁴ Immiscible: liquids that cannot mix with each other.

⁵ Ultramafic: dark coloured rocks containing almost entirely iron- and magnesium- bearing minerals and virtually no felsic minerals such as quartz and feldspar.

Major deposit classes

Sediment hosted deposits

These deposits are primarily worked for copper with cobalt as a by-product. They account for over 50 per cent of world cobalt mine production. Major deposits are characterised by ore minerals contained within organic-rich pyritic shales and sandstones deposited in a near-shore lagoonal environment, under reducing conditions. These mineralised sediments are always found above oxidised terrestrial clastic sediments. The largest deposits are found within sequences deposited during the Upper Proterozoic (approximately 1500 to 600 Ma⁶) and Permian and Triassic periods (300 to 200 Ma) due to the large areas of arid and semi-arid environments present at the Earth's surface at these times.

Two of the largest and most well known deposits of this type are the European Kupferschiefer and the Central African Copperbelt (Figure 2).

The Central African Copperbelt is the world's most important cobalt resource. It runs more than 500 kilometres across north-western Zambia and the south-east part of the Democratic Republic of Congo and is estimated to contain about six million tonnes of cobalt (Cailteaux, 2004), generally at grades between 0.17 per cent to 0.25 per cent cobalt. The mineralisation processes are not fully understood but the most widely accepted model of ore genesis is that metal concentration began with erosion of Palaeoproterozoic⁷ and Archaean⁸ basement terrains rich in cobalt, copper, nickel and gold and the influx of these sediments into a basin. Metals were further concentrated by evaporation in an arid climate. Subsequently during a rise in sea level, oxidising mineralising brines⁹ from hyper-saline lagoons were mixed with interstitial¹⁰ reducing water, rich in organic compounds. The onset of a reducing environment within the sediments triggered crystallisation of syngenetic¹¹ and early diagenetic copper and cobalt sulphides from sea-water sulphates (Cailteaux, 2004). Some of these deposits were later reworked by metamorphic processes, further increasing metal grades. The mineralised sediments are all tidal and intertidal facies, principally dolomites, dolomitic shales, black shales and sandstones.

The European Kupferschiefer also contains major sediment-hosted base metal deposits. They are rich in copper and silver,

with cobalt contents typically 20–30ppm and 100–300ppm in cobalt-enriched zones. The Upper Permian (around 250 to 256 Ma) Kupferschiefer extends from north-east England across the North Sea to Poland with most deposits located in central Germany and Lower Silesia, Poland. Other important sedimentary cobalt deposits include Mount Isa, Australia and Kilembe, Uganda, which are both also worked for their gold contents (Smith et al., 2001).

Hydrothermal and volcanogenic deposits

This deposit type groups together a wide range of deposit styles and mineral assemblages. The key process is precipitation from hydrothermal fluids passing through the host rock often sourced from, or powered by, volcanic activity. Ores can be found where minerals have been remobilised along fault planes, in veins, fissures and cracks, or as metasomatic replacement¹² of host rocks. Some major examples of hydrothermal and volcanogenic deposits, most of which have been historically worked for cobalt, are listed in Table 4.

In all these examples cobalt is a by- or co-product of mining polymetallic ores. The Moroccan Bou Azzer deposit is a significant cobalt resource and hosts the only mine in the world where cobalt is produced as a primary product. Here cobalt arsenides were formed by serpentinitisation¹⁵

Type	Major Deposit
Ophiolite ¹³ -hosted massive sulphide (Outokumpu type)	Keretti, Finland; Deerni, China; Outokumpu district, Sweden.
Ophiolite-related cobalt arsenide	Bou Azzer, Morocco.
Epigenetic ¹⁴ Au-Co-U bearing sulphides	Kuusamo, Finland; Great Bear Magmatic zone, Canada.
Epigenetic Cu-Au-Co	Idaho Cobalt Belt, USA; Greenmount, Australia.
Iron oxide-hosted polymetallic (Olympic Dam Type)	NICO and Sue-Dianne, Canada; Olympic Dam, South Australia.
Five element (Ni-Co-Ag-As-Bi) veins	Cobalt-Gowanda and Thunder Bay, Canada; Kongsberg-Modum, Norway.

Table 4 Division and major examples of hydrothermal and volcanogenic cobalt deposits (Adapted from Smith, et al., 2001).

⁶ Ma: million years ago

⁷ Palaeoproterozoic: a geological time period from 2500 Ma to 1600 Ma.

⁸ Archean: a geological time period from 4000 Ma to 2500 Ma.

⁹ Brine: water saturated or close to saturation with salt.

¹⁰ Interstitial: fluid contained within the pores or between the grains of a rock.

¹¹ Syngenetic: a deposit formed at the same time as the host rocks.

¹² Metasomatic replacement: a metamorphic process where the chemical composition of the host rock is changed via fluid flow.

¹³ Ophiolite: a section of the Earth's crust and upper mantle uplifted by tectonic forces.

¹⁴ Epigenetic: where a mineral deposit forms after the formation of the host rock.

¹⁵ Serpentinisation: the process of hydrothermal alteration of minerals in peridotite.

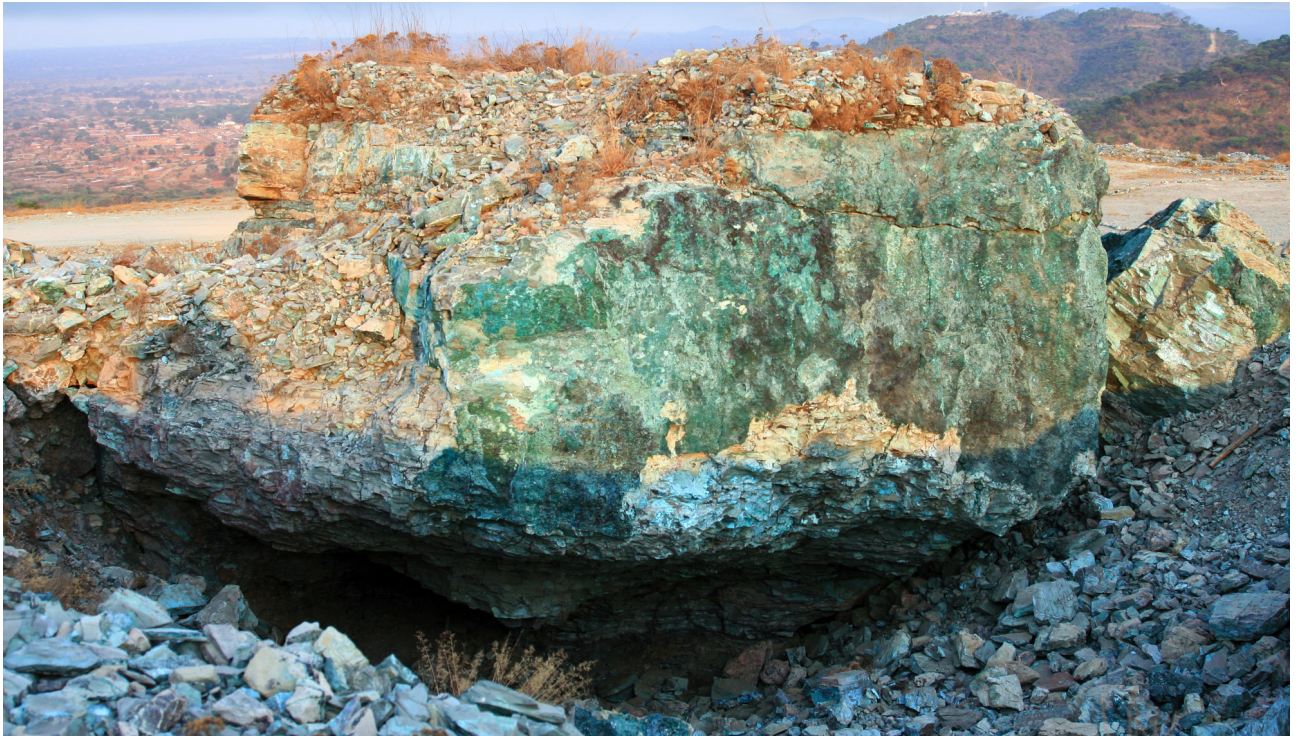


Figure 2 Copper-cobalt ore at the Tenke Fungurume deposit, Democratic Republic of Congo, an example of mineralisation within the Central African Copperbelt. Courtesy of Freeport McMoRan Copper and Gold Inc.

of cobalt-rich peridotites¹⁶ in an ophiolite complex formed during the Pan-African deformation event (around 685 Ma). These were further enriched by weathering processes and finally remobilised into economic concentrations during the Hercynian Orogeny¹⁷. The metals were recrystallised and deposited into faults and fractures. The cobalt is principally found in the mineral skutterudite (Figure 1). High levels of copper, molybdenite and gold are also locally present at Bou Azzer.

The Outokumpu district in Sweden also produced cobalt as a primary product until operations ceased in 1994. However, a mine is currently under development at Kylylahti which contains around 7.85 million tonnes of ore grading 1.17 % copper, 0.24 % cobalt, 0.22 % nickel, 0.48 % zinc and 0.70 grams per tonne gold and could begin production in 2010 (Peltonen, 2006). With Outokumpu-style deposits it is thought that economic concentrations of cobalt are created by the formation of a copper-rich proto-ore as a result of hydrothermal circulation at a mid-ocean ridge (Peltonen, 2006). This section of oceanic crust was thrust up over continental crust and the associated metasomatism¹⁸ caused the release of nickel- and cobalt-rich fluids. These mixed with the copper proto-ore and

minerals were further remobilised by regional deformation. Mineralisation is principally in the form of sulphides and cobalt can be found replacing nickel. There are 11 known deposits within the Outokumpu district with an estimated cobalt content of 500 000 tonnes (Smith, et al, 2001).

Magmatic sulphide deposits

If a mafic¹⁹ to ultramafic melt becomes saturated in sulphur (generally because of contamination from crustal-derived sulphur), an immiscible liquid sulphide phase will form, into which nickel, cobalt and platinum-group elements (PGE) preferentially partition. These elements are thus scavenged from the residual magma and are deposited in discrete sulphide-rich layers.

Magmatic sulphide deposits cover a wide range of morphologies, ages and mineralisation styles. The most common types are:

- **basal deposits**, in which sulphur saturation of mafic magma causes dense cobalt and nickel sulphides to be concentrated in basal sections of magma chambers.
- **stratabound deposits**, in which, fractional crystallisation²⁰ in large gabbroic magma chambers²¹

¹⁶ Peridotite: a rock comprised of ≥40 % olivine, with or without other mafic minerals but containing little or no feldspar.

¹⁷ Hercynian Orogeny: a mountain-building event between the late Carboniferous and early Permian ending approximately 290 Ma.

¹⁸ Metasomatism: the process of the rock interacting with aqueous fluids by which minerals of different chemical composition may grow; the rock remains in a solid state.

¹⁹ Mafic: dark coloured rocks containing iron and magnesium-bearing minerals e.g. olivine.

²⁰ Fractional crystallisation: the precipitation and segregation of minerals from magma. The residual magma and minerals subsequently crystallising progressively change chemical composition.

²¹ Magma chamber: a reservoir of molten rock beneath the Earth's surface.

causes deposition of discrete sulphide layers containing cobalt, nickel, copper and platinum-group minerals.

- **deposits in extrusive ultramafic rocks.** Komatiite²² flows become sulphur saturated by differentiation and host rock assimilation. Dense cobalt, nickel and platinum-group minerals are deposited in depressions in footwall rocks.

Generally the metal-rich layers will be found as lenses at or near the base of intrusions where the dense sulphide minerals have settled out from the lighter silicate-rich host rocks. Many of these deposits are very old; and occur in rocks of Proterozoic and Archean age (4000 to 2500 Ma). Subsequent alteration by tectonic and metamorphic forces commonly remobilises the ore minerals into elongate masses or veins of sulphide-matrix breccias (Smith et al., 2001).

Mineralisation is generally in the form of massive, interstitial or disseminated²³ sulphides. The main minerals are pyrrhotite, pentlandite and chalcopyrite, all of which can contain cobalt in substitution for other metals. Specific cobalt sulphides, such as linnaeite or carrollite, are generally restricted to remobilised vein deposits.

The largest and most economically important magmatic sulphide deposits include:

- **Noril'sk, Russia, (basal deposit).** Here deep-sourced metal-bearing magmas ascended along regional fractures to high levels in the crust where they interacted with sulphur-bearing sedimentary rocks, such as evaporites²⁴. This led to the separation of an immiscible sulphide liquid. Continued passage of fresh magma along the same conduit, feeding the overlying volcanic pile, repeated the process and led to the production of large, high-grade Ni-Cu-Co-PGE deposits.
- **Merensky Reef, South Africa, (stratabound deposits).** Very slow cooling in a major magma chamber caused the settling out of discrete mineral phases to form extensive layers. The deposits within the Merensky Reef are mainly exploited for PGEs.
- **Kambalda, Western Australia (extrusive ultramafic deposits).** Nickel and cobalt were deposited from an immiscible sulphide liquid in rapidly crystallising ultramafic extrusive rocks. Sulphur saturation can occur either due to deep-sourced

melts being enriched in mantle-derived sulphides or due to the assimilation by magma of sulphide-rich sedimentary country rocks. Due to the high density of the sulphide phase, deposits are commonly located at the base of flows.

- **Sudbury, Canada.** The nickel-copper deposits of the Sudbury Basin in Ontario are thought to have formed as a result of a large extraterrestrial impact. This caused intense magmatism by both melting rocks on impact and subsequent unloading of the underlying mantle causing these rocks to melt. This formed a large ultramafic magma chamber with high levels of crustal contamination. Assimilation of silica-rich material caused a lowering of the solubility of sulphur in the melt and consequent sulphide mineral precipitation.

Laterite deposits

In tropical and subtropical climates intense weathering of ultramafic rocks may cause significant cobalt and nickel enrichment in surficial residual deposits known as laterites. Cobalt dispersed in silicates and sulphides within the host rock is remobilised and deposited in weathered layers as hydroxides and oxides near the surface and as silicates at deeper levels. These deposits are generally about 20 metres thick and mid-Tertiary²⁵ to recent in age. They are principally worked for nickel with cobalt as a by-product. The cobalt is contained within limonite and goethite as well as erythrite and asbolite. At deeper levels, weathering of ultramafic rocks is less intense and the nickeliferous mineral garnierite is formed.

Serpentine-rich zones in saprolite²⁶ at the base of laterites, restrict the circulation of groundwater and thus the amount of cobalt enrichment. It also interferes with the processing of the ore as individual grains need to be crushed in order to liberate ore minerals from gangue²⁷ intergrowths. Grades of cobalt in laterite deposits vary widely in the range 0.1 to 1.5 % Co.

Topography plays an important role in the formation of laterite deposits. The most extensive deposits are found on gently dipping slopes where groundwaters can freely circulate to encourage weathering. Therefore deposits are often associated with areas of gentle tectonic deformation causing slow uplift. Important examples are found in New Caledonia and Cuba due to large areas of serpentinised peridotites and ideal weathering conditions.

²² Komatiite: an Archean (4000 – 2500 Ma) ultramafic igneous rock, normally formed as a lava flow.

²³ Disseminated: small fine-grained particles of ore mineral dispersed through a rock.

²⁴ Evaporites: sedimentary rocks composed of minerals produced by evaporation of water e.g. gypsum and rock salt.

²⁵ Tertiary: a geological period from 65 Ma to 1.64 Ma.

²⁶ Saprolite: a fine-grained clay produced by weathering of bedrock.

²⁷ Gangue: the minerals in an ore that do not have economic value.

Manganese nodules and cobalt-rich crusts

On sediment-starved deep ocean floors, generally 4 to 5.5 kilometres deep, concretions rich in manganese, cobalt and nickel can form around small fragments of debris and organic material. The nodules concentrate minerals from siliceous oozes and from the water column. Their occurrence in proximity to mid-ocean ridges suggests a volcanogenic source for mineral enrichment. They may occur as densely packed sheets covering areas of hundreds of square kilometres with cobalt grades in the range of 1 to 2.5 per cent.

Cobalt-rich crusts form in a similar way with minerals precipitating out of sea-water, possibly with the aid of bacterial activity, into crusts up to 25 centimetres thick. Cobalt-rich crusts form at shallower depths (around 0.4 to 4 kilometres) than manganese nodules on the flanks and summits of seamounts (ISA, 2007). Accretion rates for cobalt-rich crusts and nodules are some of the slowest natural processes on the planet and can be as slow as one to six millimetres of growth every one million years.

It is estimated that the resources of cobalt in these nodules and crusts may be comparable with land-based resources. However, due to political uncertainties regarding ownership of the oceans and problems associated with extraction in deep-sea water, these resources remain uneconomic.

Extraction methods and processing

Extraction

Cobalt is almost always extracted as a by-product of other minerals, usually copper or nickel. A detailed description of the relevant extraction techniques for these metals can be found in the Copper and Nickel commodity profiles available from www.MineralsUK.com

Depending on their size, grade, morphology and proximity to surface, deposits are mined by either underground or open-pit methods, or 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 overburden²⁸, digging the ore or blasting with explosives, then removing the ore by truck or conveyor belt for stockpiling prior to further processing.

²⁸ Overburden: the waste material, such as soil, sand, clay etc. that lies above a mineral deposit.

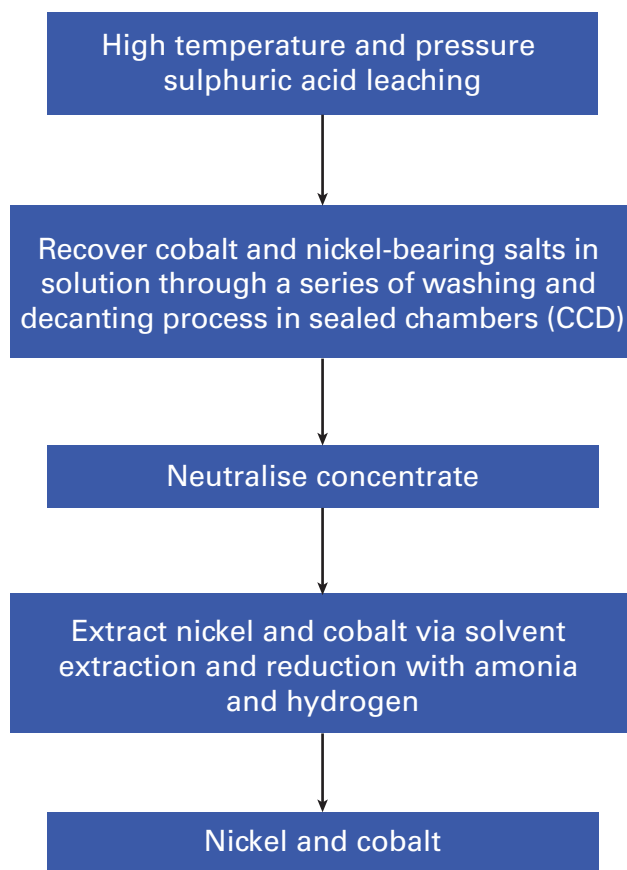


Figure 3 Flow diagram summarising pressure acid leaching, (PAL).

Underground mining

Underground extraction uses a variety of standard mining methods depending on the characteristics of the particular mineral deposit. It is suitable for extraction of higher grade or deep ore bodies. Techniques used include block caving (for large, uniform deposits), room and pillar (typically for flat, < 30° shallow dipping deposits), and other stoping methods (for narrow or steeply-dipping veins).

Opencast and underground methods are commonly 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.

Due to technological advances and increasing demand for cobalt, a new development for cobalt extraction is the re-working of areas of copper mine tailings. Many historic copper mines have large volumes of tailings with economic grades of cobalt. An example is the Kolwezi tailings project in the Democratic Republic of Congo, which is due to start production in 2010. The owner of the deposit, First Quantum, claims this could be one of the largest and lowest-cost producers of cobalt in the world

(<http://www.first-quantum.com>). The planned extraction process is simple: the solid tailings, which were created as a by-product of copper mining in the 1950s, would be broken up using high-pressure water guns and the resultant slurry pumped to a processing plant where cobalt would be extracted, by methods similar to those used with conventional ores.

Processing

After mining, ores are processed to upgrade their metal content. Concentration is normally carried out at, or close to, the mine site and involves crushing the ore and separating cobalt-bearing and gangue minerals, using suitable physical and chemical processes, collectively known as beneficiation.

Cobalt is almost always a by-product of other metals and any beneficiation processes will depend on those required for the extraction of the primary metal. Processing for cobalt generally begins only after the primary metal (usually copper or nickel) has been concentrated and extracted. The process are often unique to the mineralogy of the ore exploited. There are three basic processes used for cobalt extraction: hydrometallurgy (including solvent extraction; electrolysis and electrowinning); pyrometallurgy and vapometallurgy.

In **hydrometallurgy**, metals are separated using differences in solubility, and electrochemical properties

while in the solution. One of the most common hydrometallurgical processes is pressure acid leaching (PAL). PAL involves preheating the slurried ore and mixing it with concentrated sulphuric acid at high temperature and pressure. Typical conditions are 255°C and 4.4 million pascals. After 90 minutes or so under these conditions, nickel (usually the primary metal extracted in this procedure) and cobalt are converted to soluble sulphate salts. These are then fed into a counter-current decantation circuit (CCD). CCD involves several stages of washing the nickel and cobalt enriched slurry to produce a clear solution of nickel and cobalt and a solid residue. Nickel, cobalt and other sulphides are precipitated in the next stage, through a reaction with injected hydrogen sulphide. The mixed metal sulphide is refined through re-leaching with oxygen at high pressure. This converts the sulphide to a metal sulphate phase. Iron and copper are then removed using chemical reactions with ammonia and air, and sulphuric acid, respectively and the cobalt is separated from the nickel using an organic reagent. PAL is most suitable for ores low in magnesium and aluminium, which require lower acid consumption.

There are several methods of recovering cobalt after pressure acid leaching has removed primary metals. At the Goro laterite deposit in New Caledonia, solvent extraction is used after heap leaching of the ore. This technique uses a solvent, known as an extractant, to concentrate



Figure 4 Smelting for copper and cobalt at the Mount Isa Mine, Australia. Reproduced by kind permission of Xstrata.

the material (in this case cobalt) based on the difference in solubility of the material being extracted within two immiscible liquids. For the Goro deposit, first the acid metal-rich solution from the PAL process is neutralised and impurities and by-products such as copper and zinc are removed. Any remaining impurities are subsequently removed by two stages of solvent extraction with an organic solvent. Hydrochloric acid is then used as an extractant to separate out nickel and to form cobalt chloride, which is neutralised by adding sodium carbonate. This process forms cobalt carbonate crystals which can then be filtered out of the acid.

At the Murrin Murrin deposit, Western Australia, cobalt is extracted from a nickel/cobalt sulphide solution. The cobalt is first separated from nickel using ammonia as a reagent, and then the resultant solution is fed into an autoclave where it is reduced by hydrogen under high pressure. The solid cobalt powder is then separated, filtered and dried.

Electrowinning processes involve filtration of the metal-rich solution, heating, and then a series of electrolytic stages. The cobalt precipitates onto stainless steel starter sheets to form high-purity cathodes and the acid is then recycled.

Electrowinning processes are employed by the Chambishi plant in Zambia which processes many of the ores from the Zambian Copperbelt mines. Copper is first recovered by electrowinning, then cobalt is precipitated out of the electrolytic solvent as a carbonate. This is re-dissolved in spent electrolyte, which is fed back into the electrowinning tanks to recover the cobalt metal.

Vapometallurgy is a modern process that is effective for processing lateritic ores. Nickel and cobalt metal can be recovered and refined directly from the ore, matte or concentrate. The metal in the ore is vaporised chemically using carbon monoxide and other gases. This vapour then passes to a separate chamber where metal is deposited. This is a streamlined process which mainly operates at atmospheric pressure.

In **pyrometallurgical** processes, heat is used to separate metals based on differences in melting points, densities and other physical and chemical characteristics. These methods are mainly used for magmatic sulphide ores and rely heavily on smelting to recover as much metal as possible from the concentrate (see Figure 4). Flash smelting is commonly used, where dry concentrates are fed into the furnace with a preheated air or oxygen mixture. An exothermic

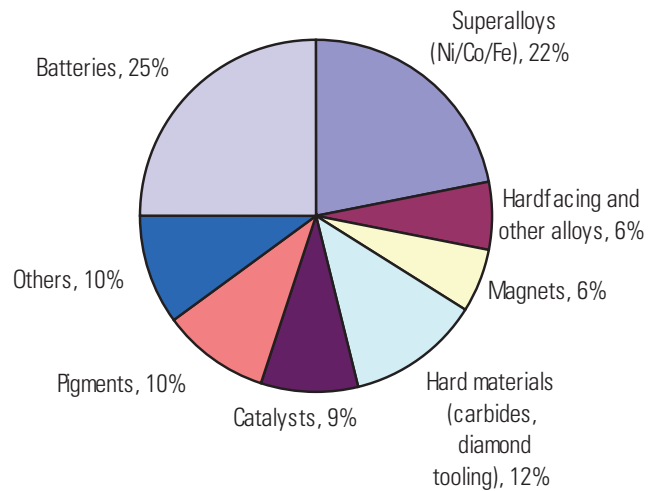


Figure 5 Global end use of primary cobalt (adapted from the CDI).

reaction produces enough heat to smelt the concentrate and produces liquid matte and slag²⁹. Nickel and cobalt are recovered as a sulphide matte, while iron is recovered in slag and sulphur in sulphur dioxide gas. Smelting can produce a variety of nickel/cobalt products such as carbonates and oxides. Cobalt is usually extracted from these smelting products using electrolytic processes where a cobalt anode³⁰ dissolves in an electrolytic cell and deposits cobalt ions onto a cathode³¹ with any impurities settling to the bottom of the cell.

Manufacturing

Cobalt is commonly produced as powders, briquettes, cathodes, rounds and ingots depending on its final end use. Powders can be easily dissolved and melted and are generally more suited for chemical processes, whereas cathodes and ingots are more appropriate for metallurgical end uses.

Specifications and uses

Specification

Cobalt is produced in a wide variety of forms, including:

Refined cobalt

Refined cobalt metal consists of almost pure (98 to 99 per cent) cobalt with minor amounts of nickel, copper and iron. The Cobalt Development Institute (CDI) defines refined cobalt as 'all cobalt units, whether in metal or chemicals derived from feed requiring further refining'.

Cobalt matte

Matte is an intermediate product of smelting which is used in the preparation of refined metal. It comprises a

²⁹ Slag: waste material, which floats to the top during smelting operation.

³⁰ Anode: the positive electrode in an electrochemical cell.

³¹ Cathode: the negative electrode in an electrochemical cell.



Figure 6 Rechargeable batteries which may contain significant quantities of cobalt.

mixture of cobalt, copper, nickel and iron sulphides either in the form of black granules or as a consolidated mass. The majority of matte never enters the market and is refined to a purer form. Cobalt content in matte is around 1.5 to 2 per cent.

Cobalt alloys

These are mixtures of metals in which cobalt is the dominant metal by weight. There are many different alloys of cobalt.

Cobalt chemicals

Numerous cobalt chemicals are marketed, including oxides, hydroxides, carbonates and sulphates.

Uses

As pure metal, cobalt has a very limited range of uses, but it is extensively used as an alloying metal. It is valued for its ability to produce very hard superalloys with useful magnetic properties and resistance to high temperatures. Cobalt is used in the manufacture of chemical compounds for a wide range of industrial uses. Rechargeable batteries consume the largest proportion of cobalt in this sector. It is also used as a pigment in glass, enamels, pottery and china.

Superalloys

When mixed with certain other metals cobalt can produce 'superalloys' which are capable of withstanding severe

mechanical stresses and temperatures. When cobalt is added to nickel-based alloys it alters the molecular structure of the alloy and thus enhances their high temperature strength (for which they are principally valued) and their resistance to chemical corrosion. These properties make cobalt superalloys ideal for use in jet engines and other turbines where high temperatures are encountered. A smaller proportion of superalloys are manufactured for use in chemical applications where resistance to corrosion is critical.

Magnetic alloys

Cobalt can be alloyed with several other metals to produce specialised magnets, with applications in high performance electrical equipment. Cobalt has the ability to improve the magnetic properties of iron and also has the highest known Curie point (the temperature at which the magnetic field begins to be lost) of 1121°C.

One of the most versatile cobalt-based magnetic alloys is the aluminium-nickel-cobalt alloy known as Alnico. Alnico may vary greatly in composition from 5 to 38 per cent cobalt, and can also contain iron, copper, titanium, zirconium and niobium. These alloys have high mechanical strengths and operating temperatures of up to 550°C. They can also be cast³² into complex shapes, although they are brittle and cannot easily be machined.

³² Cast: metal shaped in casting moulds when molten.

Cobalt can also be alloyed with samarium³³ to produce a very powerful magnet with operating temperatures of about 350°C. However, due to high manufacturing costs, samarium magnets are now often replaced by other non-cobalt alloys. Magnetic cobalt alloys can be found in a wide range of applications including motors and generators, telephones, microphones, automotive sensors, loudspeakers and computer hard disc drives.

Other cobalt alloys

There is a broad spectrum of uses for other alloys which use cobalt to impart beneficial properties:

- **high-speed steels.** Cobalt is a component in modern, high-specification, high-carbon steel cutting tools where the cobalt imparts stability at high temperatures enabling the tools to cut faster and for longer periods.
- **hard facing materials.** Cobalt can be used to give hard and corrosion resistant coatings. This can be achieved by coating a material in carbide containing up to 17 per cent cobalt.
- **prosthetic limbs.** Some prosthetic hips and new joints can contain up to 62 per cent cobalt, in the form of cobalt-chrome-molybdenum alloys which have a high strength and good biocompatibility.

- **low expansion alloys.** Substituting cobalt for nickel in nickel-iron alloys produces a low expansion cobalt alloy. The most widely used is known as super-invar. This has applications in the electronic packing industries and can produce hermetic seals which can withstand temperature ranges of -55°C to +55°C.
- **maraging steel.** Cobalt can also be used to make steels which, although they do not have as high a specification as many other steel types, are easily produced and machinable while maintaining a high level of strength. These are known as maraging steels and are used primarily for aerospace and military applications.

Batteries and electronics

Cobalt is also an important component of the three main rechargeable battery technologies; nickel-cadmium batteries: nickel-metal hydride batteries and lithium-ion batteries, with the highest proportion of cobalt found in high-performance models.

In **nickel-cadmium** batteries the cathode³⁴ (formed from nickel hydroxide) can contain between one and five per cent cobalt in the form of a fine powdered oxide or hydroxide. The cobalt improves conductivity, adds mechanical stability and increases performance in the electrolyte.



Figure 7 Construction of the Tenke Fungurume operation, a copper-cobalt deposit located in the Democratic Republic of Congo. Courtesy of Freeport McMoRan Copper and Gold Inc.

³³ Samarium: a rare earth metal, with symbol Sm and atomic number 62.

³⁴ Cathode: the negative electrode in an electrochemical cell.

The basis of **nickel-metal hydride** technology is the ability of nickel hydride alloys (used as cathodes) to store hydrogen. The nickel alloys can contain up to 15 per cent cobalt which chemically stabilises the battery, inhibits corrosion, and can greatly enhance the life of the battery.

Lithium-ion batteries contain much higher amounts of cobalt with up to 60 per cent of the cathode composed of cobalt in the form of lithium-cobalt oxide. This type of battery works by the exchange of lithium ions between non-metallic lithium compounds and is both lighter and more powerful than the other types.

Cobalt also has several other applications in electronics. For this purpose cobalt is alloyed with silicon to produce a metal silicate with low resistivity, high thermal stability and good bonding properties which is used for electrical connectors on integrated circuits. High quality electrical contacts can contain up to 15 per cent cobalt, which is co-deposited with gold to increase resistance to wear.

Chemicals

Cobalt has a wide range of chemical applications, ranging from medicinal to industrial. Catalytic processes account for around nine per cent of total cobalt usage, equivalent to 2700 tonnes of cobalt a year (CDI) (Figure 5). The vast majority of this is consumed by the petrochemical industry where a cobalt oxide compound is used to remove sulphur from crude oil in the refinery process. Cobalt based catalysts are also employed in gas-to-liquid technology where natural gas is processed to synthetic diesel fuel; a sector predicted to rapidly increase in the future. Cobalt-based acetate/manganese sodium bromide catalysts are also used in the production of plastics (CDI).

Other uses

Historically one of the most important uses of cobalt was as a pigment and this application still accounts for around nine per cent of cobalt usage. Cobalt can be used to impart striking colours from light blue to black depending on the compounds used. The main application for this is in ceramics but it is also used in glass, porcelain, paints and inks.

Cobalt salts are widely used in agriculture as a supplement to animal feeds to prevent anaemia in livestock.

The cobalt isotope ^{60}Co is a strong gamma ray emitter, with a half-life of 5.27 years. It is employed mainly in medicine, where it can target cancer cells in radiation therapy, but can also be used for flaw detection for mechanical purposes. Cobalt isotopes are also used in medicine as a radioactive tracer.

World resources

According to the USGS, world identified resources of cobalt metal are estimated at 15 million tonnes, excluding the cobalt contained in deep sea nodules and crusts on the sea floor (see Table 5). The Cobalt Development Institute estimates suggest that the latter may contain between 2.5 and 10 million tonnes of cobalt.

Current world reserves are estimated at 7 million tonnes, nearly half of which are found in the Democratic Republic of Congo (Table 5).

Country	Reserves ('000 tonnes)	Percent share
Congo, D.R.	3400	47.9
Australia	1500	21.1
Cuba	1000	14.1
Zambia	270	3.8
Russia	250	3.5
New Caledonia	230	3.2
Canada	120	1.7
China	72	1.0
United States	33	0.5
Brazil	29	0.4
Morocco	20	0.3
Rest of the world	180	2.5

Table 5 World cobalt reserves in 2008. Source: USGS.

World production

Cobalt is extracted in about 14 countries, mainly as a by-product of copper and nickel mining. According to the CDI, in 2007, 48 per cent of the world's cobalt was extracted as a by-product of nickel mining. Morocco is currently the only producer of primary cobalt (from cobalt arsenide minerals), although potential additional sources in Cameroon, USA and Zambia are being investigated. Total world mine production of cobalt in 2007 was approximately 61 000 tonnes (cobalt content of concentrates), three per cent less than the amount produced in 2006. Over 40 per cent of the world's cobalt ore is mined in the Democratic Republic of Congo where an estimated 25 300 tonnes were produced in 2007 (almost 2000 tonnes less than the amount produced in 2006). Canada, Australia and Russia produce almost another third of world production between them (Figure 8). Notably, Russian production dropped 25 per cent from 2006 to 2007, while Canadian production increased by 16 per cent during the same time frame.

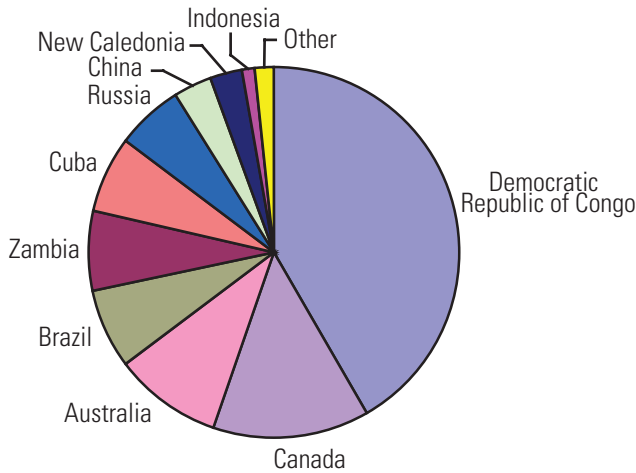


Figure 8 World mine production of cobalt 2007 (metal content). Source: British Geological Survey, World Mineral Production 2003–2007.

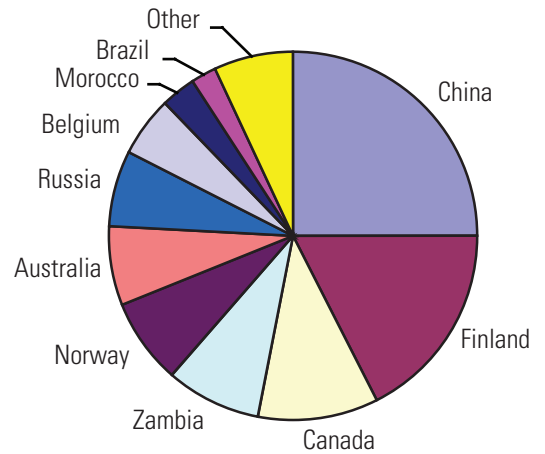


Figure 9 World refined production of cobalt metal in 2007. Source: British Geological Survey, World Mineral Production 2003–2007.

In 2007, total world production of refined cobalt was 52 900 tonnes (shown in Figure 9), a one per cent decrease on the 2006 total. One quarter of the world's refined cobalt comes from China where more refined cobalt metal than cobalt ore is produced. China has secured many life-of-

mine or long-term contracts with cobalt producers in other countries (such as Australia and the Democratic Republic of Congo) to ship cobalt concentrates to China to ensure sufficient supply to their smelters. Refined cobalt production from Finland and Norway (combined) makes

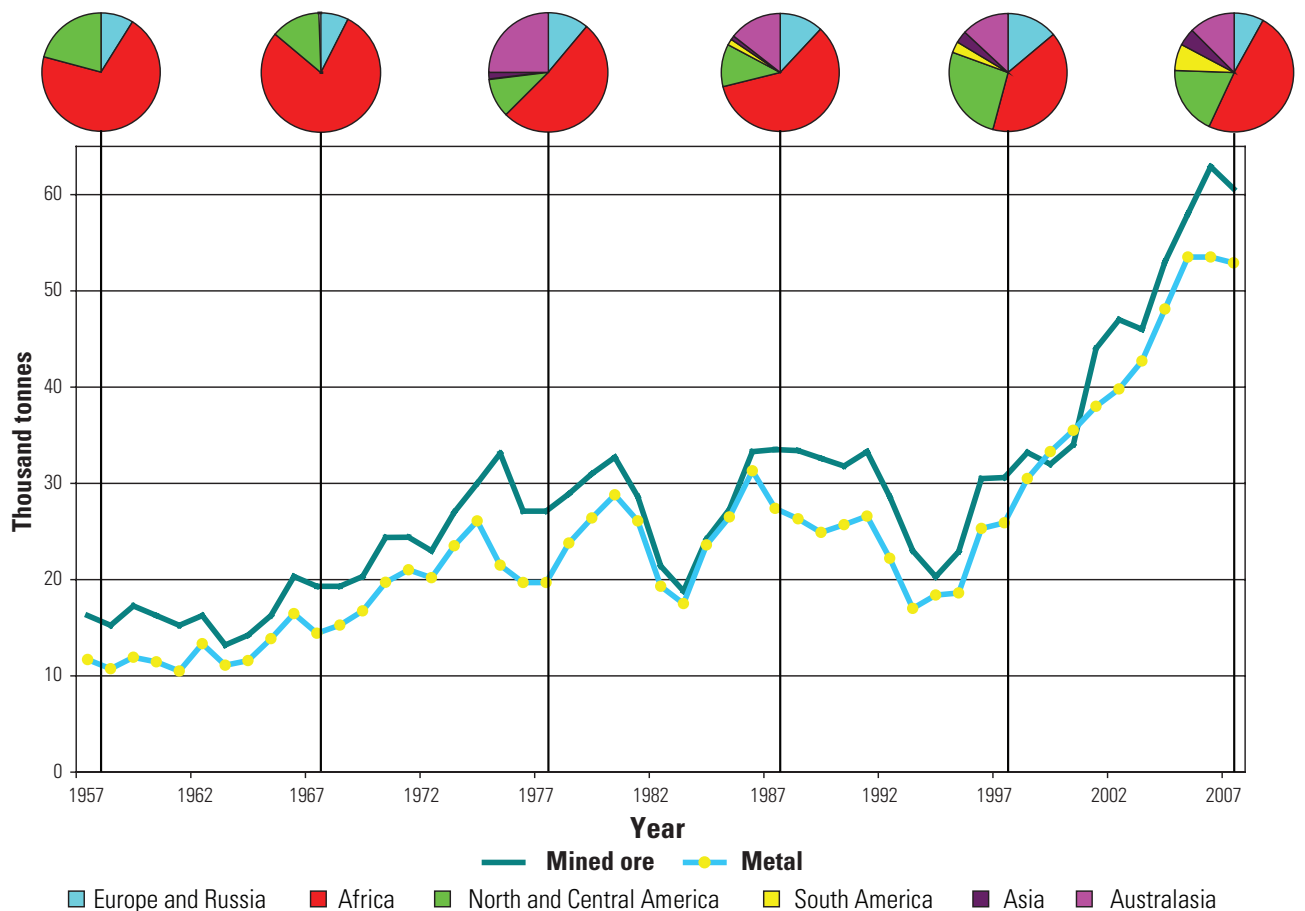


Figure 10 World production of mined ore and refined cobalt metal 1957 – 2007. Pie charts show percentage mined in each region at 10 year intervals. Source: British Geological Survey, World Mineral Statistics.

up a further quarter of world cobalt metal production, although neither country mines cobalt themselves. In 2007, 38 per cent of refined cobalt production was based on imported material processed by countries that do not mine cobalt ore.

Cobalt production (of both mined ore and refined metal) has doubled in the last ten years, as shown in Figure 10. Africa has historically been the major centre for cobalt production and 50 years ago around three quarters of the cobalt ore produced came from Africa. Since then, although African production has almost tripled, today it accounts for just under half of total world production. Output has fluctuated due chiefly to political instability in the producing countries. Despite this, production from the Democratic Republic of Congo has reportedly almost doubled in the last five years, with new mines coming on-stream. Asian output has also increased in the last five years, where Chinese production has doubled, albeit at an order of magnitude less than the production increases of the Democratic Republic of Congo. Mine production from the Americas has been ramping up over the last 20 years. Brazil's output almost quadrupled to current levels since the late 1990s and Cuba has also increased its production in recent years.

Only about 75 per cent of total mine production is recovered as marketable product. Often the rates of cobalt recovery from nickel laterite ore are low and only a fraction of the total is recovered. However, this situation is changing due to advances in heap leaching and other processing technology.

The USGS reported that 'secondary' (recycled) production in the USA amounted to an estimated 1860 tonnes in 2008, 20 per cent of the reported consumption. This is probably higher than the world average due to the importance of the US aerospace industry, which is a major source of scrap in the form of superalloys.

World trade

In September 2008 the London Metal Exchange (LME) announced plans to trade cobalt on the metal exchange from the second half of 2009. Until that time, cobalt is traded on the free market. Many of the sales occur over the internet, where it is sold via the websites of major market players. However as of December 2008, prices are no longer displayed publicly. Previously three main companies displayed cobalt prices:

- BHP Billiton's Cobalt Open Sales System (<http://cobalt.bhpbilliton.com>): ceased displaying prices in December 2008.

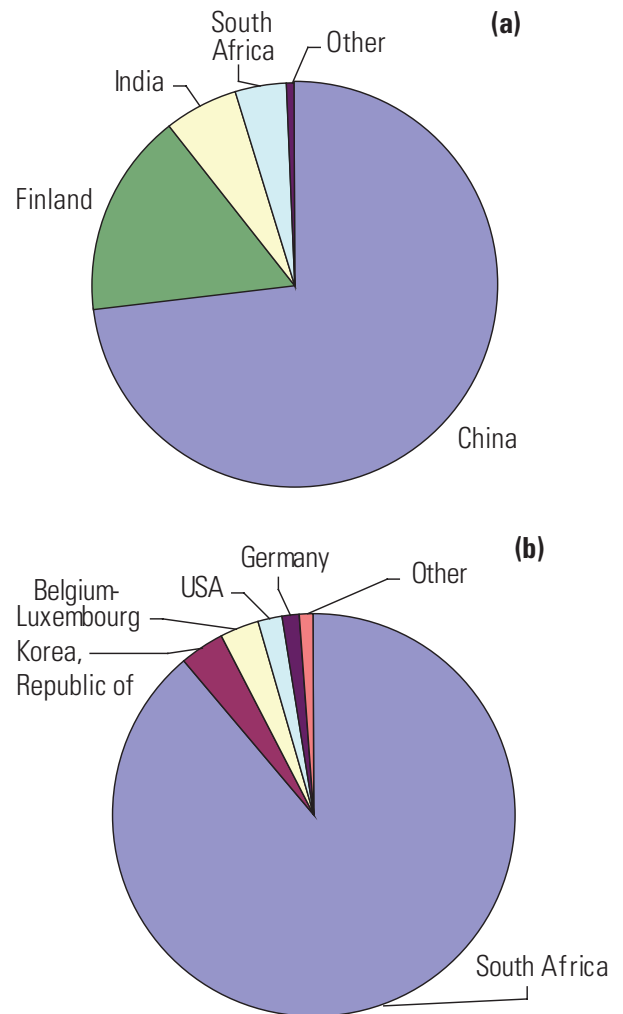


Figure 11 World trade in cobalt ore in 2007 (a) Imports (b) Exports. Source: British Geological Survey, *World Mineral Statistics*.

- Jinchuan Group website (www.jnmc.com)
- Noril'sk Nickel: suspended its cobalt pricing website in August 2008.

Cobalt is generally traded in two grades: as 99.8 per cent cathode (high grade — usually from North America and Europe, often colloquially termed 'Falconbridge (Xstrata) cathode' by traders); and 99.3 per cent (low grade — from Russia, termed 'K1Ay ingot'). However, cobalt from Zambia is usually around 99.6 per cent (e.g. 'Mopani cathode') and output from the Jinchuan Group is typically 99.5 per cent pure.

China is the largest importer of cobalt ore (120 000 tonnes in 2007 (see Figure 11), which represents almost three quarters of total world imports). They have many life-of-mine contracts with African producers to supply their smelters. Much of the cobalt they refine is used domestically. There is a continuing demand from the chemical sector for cobalt salts to fuel the Asian battery market. Demand for cobalt for superalloys increased in

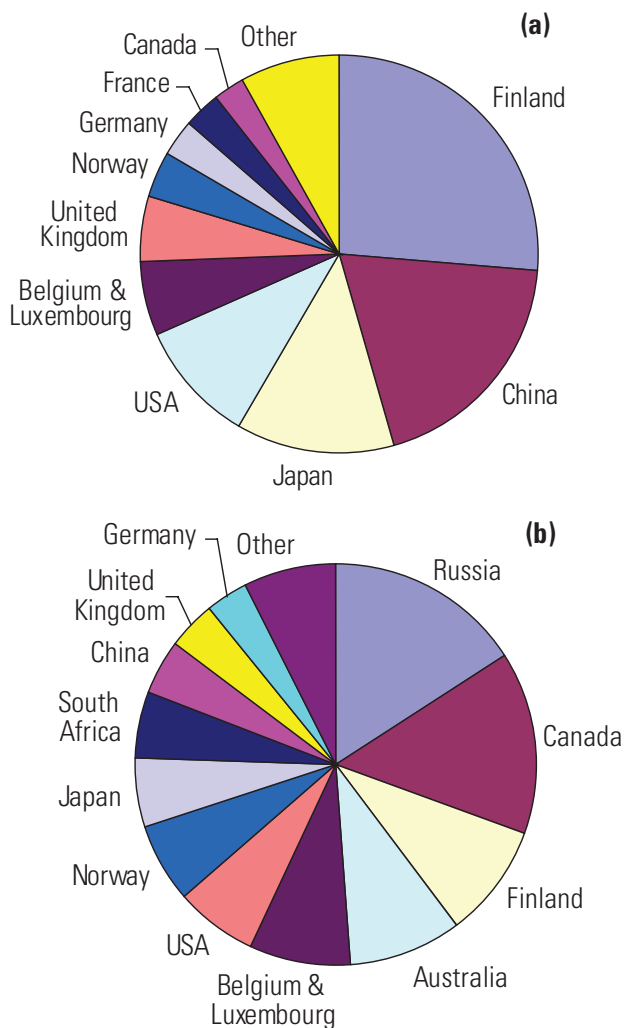


Figure 12 World trade in cobalt metal in 2007 (a) Imports (b) Exports. Source: British Geological Survey, World Mineral Statistics.

the last five years reportedly to 22 per cent of all cobalt demand (CDI).

The majority of African cobalt ore production is routed through South African ports for export. In 2007, 33 000 tonnes were exported via this route, which accounts for almost 90 per cent of total world exports. Much of the ore produced in the DRC is treated in Zambia and then exported to China via the South African ports. However, a government ban on exporting raw ore from Katanga province was issued in early 2007. This was an attempt to add value to the raw ore before it left the country, but insufficient smelter capacity meant the ore could not be refined quickly enough. Consequently this ban was lifted in early 2009. Total world cobalt ore exports in 2007 were more than double that in 2006.

Cobalt metal trade is less dominated by individual countries compared to trade in cobalt ore. It also appears to be more stable because year on year differences are

smaller compared to the large fluctuations seen in ore trading volumes. This is thought to be primarily due to political situations affecting ore production and delivery, in comparison with the more stable demand for the end product. In 2007, Finland and China were the top importers of cobalt metal, (importing 28 000 and 20 000 tonnes respectively) and together they account for almost half of world cobalt metal imports. The UK imports around five per cent of the total world cobalt metal imports (5400 tonnes in 2007). Canada and Russia each exported almost 10 000 tonnes of cobalt metal in 2007, both more than 25 per cent higher than 2006 tonnages. The UK exported 2300 tonnes of cobalt metal in 2007, which is around four per cent of the total world cobalt metal exports.

Prices

Cobalt prices have long been volatile. Prices have surged and then dropped in the last two years, (as shown in Figure 13). Average prices in 2008 were 30 per cent higher than the previous year, despite the monthly average price for December 2008 having dropped by 60 per cent year-on-year to US\$14.5 per lb. The price for high grade cobalt peaked at over US\$50 per lb in March 2008 (Metal Bulletin).

The price drop which began in October 2008 is primarily in response to the recent global economic downturn. However, analysts had been predicting a drop in cobalt prices due to a surplus in supply from new mines. By December 2008 the low cobalt prices had forced closure of many uneconomic projects and mines.

Supply of cobalt ore continues to be strongly controlled by the situation in the Democratic Republic of Congo and around half of the new projects due to come on stream within the next few years are located there. During 2008, the government initiated mine-contract renegotiations citing undervaluation of resources. A ban (now lifted) on exports of raw ore from Katanga province was also in place throughout 2008 in an attempt to add value to the ore in-country.

In previous years, the US Defence Logistics Agency (DLA) stockpile has contributed to supply. However this is now very low, if not exhausted, and its contribution to supply is insignificant.

Prices of refined cobalt are strongly controlled by demand from the chemical sector, particularly for growing applications such as rechargeable batteries and as a catalyst in gas-to-liquid technology.

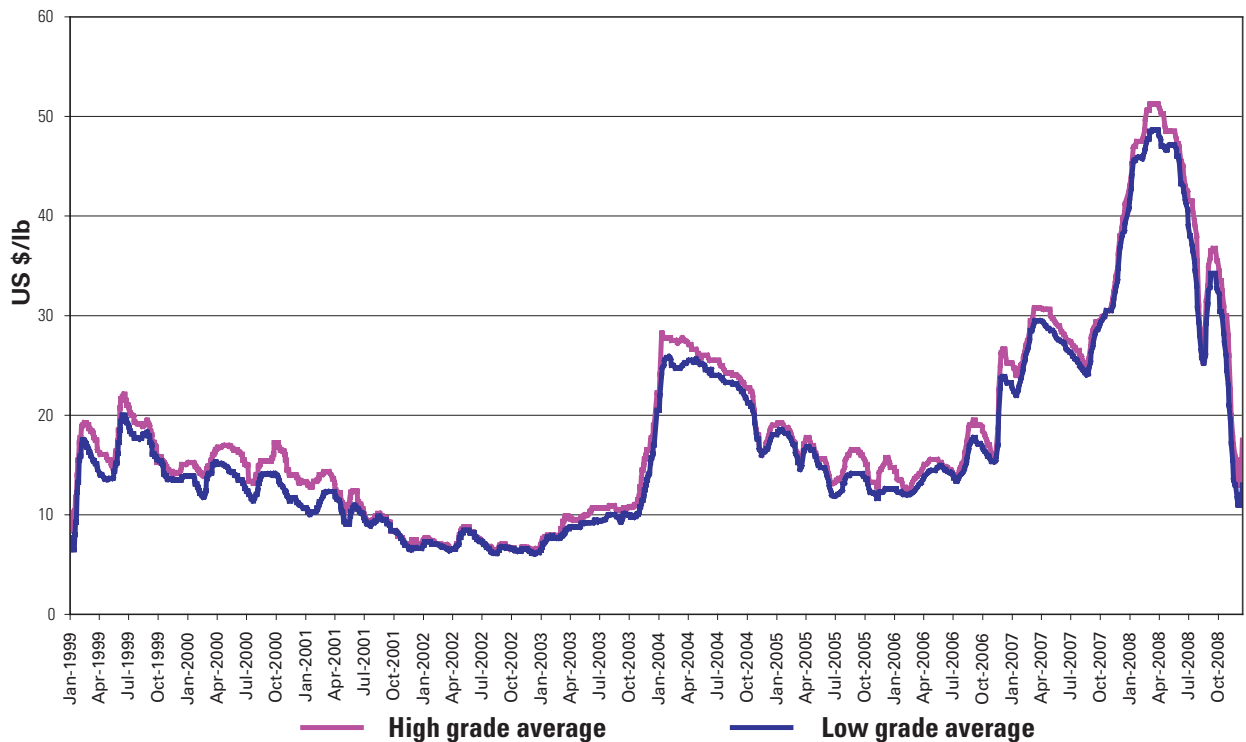


Figure 13 World cobalt prices 1999–2009. (free market US\$ per lb in warehouse). Courtesy of Metal Bulletin (www.metalbulletin.com)

Alternative technologies

Recycling

A significant proportion of cobalt is recycled due to its rarity, cost benefits (compared to cobalt extraction from ore) and to prevent potential environmental damage caused by decomposition of batteries in landfills. The recycling process depends on the type of material being processed; most alloys are re-melted in an electric arc furnace to a uniform chemistry while cemented carbides will be disaggregated and re-used. Recycling rechargeable batteries involves incinerating the batteries, recovering the resultant alloy metal and separation of cobalt, iron, nickel and copper. Battery manufacturers seek to operate a closed loop system for rechargeable batteries so that no material is lost.

The feedstocks into the cobalt recycling process can be divided into 'new scrap' and 'old scrap'.

New scrap

This includes all waste from processing and manufacturing, before it enters the consumer market, and comprises:

- **hard scrap** — solid pieces of alloys or cemented carbide parts that are either sub-specification or generated from excessive amounts of alloy during casting, pressing or forging.
- **soft scrap** — finely divided material, such as sludge produced from grinding cobalt-containing

materials, dust from manufacturing and powders from metallurgical processes.

Old scrap

Old scrap is post-consumer waste derived from worn out or obsolete products. It is harder to collect and separate for recycling than new scrap, as it is often mixed with other materials. This scrap is usually sold to a merchant or dealer, who, in turn, sells it on to a mill or other processor for sorting. Old scrap comprises:

- **alloys** — turbine blades, jet engines, cemented carbide cutting tools and magnets removed from consumer or industrial equipment. These will often not be recycled specifically for the cobalt but re-melted and used again in the form of the original alloy.
- **rechargeable batteries** — In November 2003, the European Commission proposed new rules to ensure that almost all used batteries are collected and recycled, in a bid to prevent environmental and health problems that could be caused by disposal of them in waste incinerators or in landfill sites.

Cobalt alternatives

Alternatives for cobalt are constantly being sought due to the metal's scarcity and volatile prices. However due to the unique properties of cobalt, especially for alloying, there are limited options for substitution and almost all substitutes result in reduced product performance.

In high-hardness alloys, barium and strontium can act as potential cobalt substitutes. In high performance magnetic alloys, nickel-iron alloys have similar properties to cobalt and are occasionally used as alternatives. Nickel, which shares many of the same properties of cobalt, can also substitute to a limited extent for cobalt in cutting and wear-resistant materials, jet engine manufacture, petroleum catalysts and batteries, although this always results in a loss in performance. High performance ceramics can also be used as a replacement for cobalt alloys in applications where high temperature-resistant, high-hardness materials are required. In pigments, cerium, iron, lead, manganese and vanadium can all be used instead of cobalt to some degree.

Much research has gone into finding a replacement for cobalt compounds in batteries as these compounds can form toxic substances and may cause overheating if a short circuit occurs. Cobalt is also more expensive and generally heavier than alternatives. A cobalt-manganese-nickel compound can reduce the amount of cobalt used in batteries and the use of these compounds has greatly increased over the last few years. As a consequence, although rechargeable battery demand is expected to increase rapidly (due to increasing demand for portable electronic goods and development of hybrid cars requiring batteries), cobalt demand in this application could remain stable or even decrease slightly. New systems such as hydrogen fuel cells may also reduce the reliance on cobalt for batteries.

Focus on Britain

Cobalt-bearing mineralisation has been reported from several localities in Britain, although cobalt production is recorded from only a few sites (see Figure 14). In south-west England, cobalt was recovered from tin-copper mines at Dolcoath and East Pool, both near Camborne, and at Great Dowgas and St.

Austell Consols, near St. Stephen. In these areas the cobalt minerals occur in veins carrying bismuth, nickel and uranium ores. In the nineteenth century small amounts of cobalt were recovered from sedimentary copper deposits at Alderley Edge in Cheshire. In Scotland, in the eighteenth century, cobalt ores were mined on a small scale with silver at Silver Glen, near Alva, Perthshire. Cobalt was also reported from the Hilderston mine, near Linlithgow. The Coille-bhraghad copper mine, near Inverary in western Scotland, contained pyrrhotite with over one percent cobalt. In the Central Wales Orefield, traces of cobalt minerals occur in the silver-lead-zinc veins cutting Lower Palaeozoic³⁵ sedimentary rocks.

Britain is one of the largest consumers of cobalt metal due to the presence of a major aero-engine manufacturer, although the precise pattern of usage is unclear, due to commercial confidentiality. Cobalt metal is used by companies making high-performance alloys for the aero-engine producer and other manufacturers, and in the cemented carbide, magnet and special steel industries. The Iron and Steel Statistics Bureau records that 20 tonnes per year is used by the steel industry. Cobalt chemicals are used chiefly by glass and ceramic manufacturers.

The calculated total apparent UK consumption of cobalt ranged between 1100 tonnes and 2900 tonnes per year over the period 2003 to 2007, equivalent to 4.75 per cent of total world mine output in 2007. There is no primary production of cobalt metal in the UK but several companies produce special cobalt alloys based on imported unwrought metal and scrap. UK cobalt exports have declined 50% over the period 2003 to 2007. However despite this, the UK is the seventh largest country in the world for exports of cobalt oxides, which averaged 811 tonnes per year over the period 2005 to 2007. These originate in Canada and are processed at the nickel refinery in Clydach, South Wales, before marketing.

³⁵ Palaeozoic: a geological era from the Cambrian to the Permian period spanning the period from 542 Ma to 251 Ma.

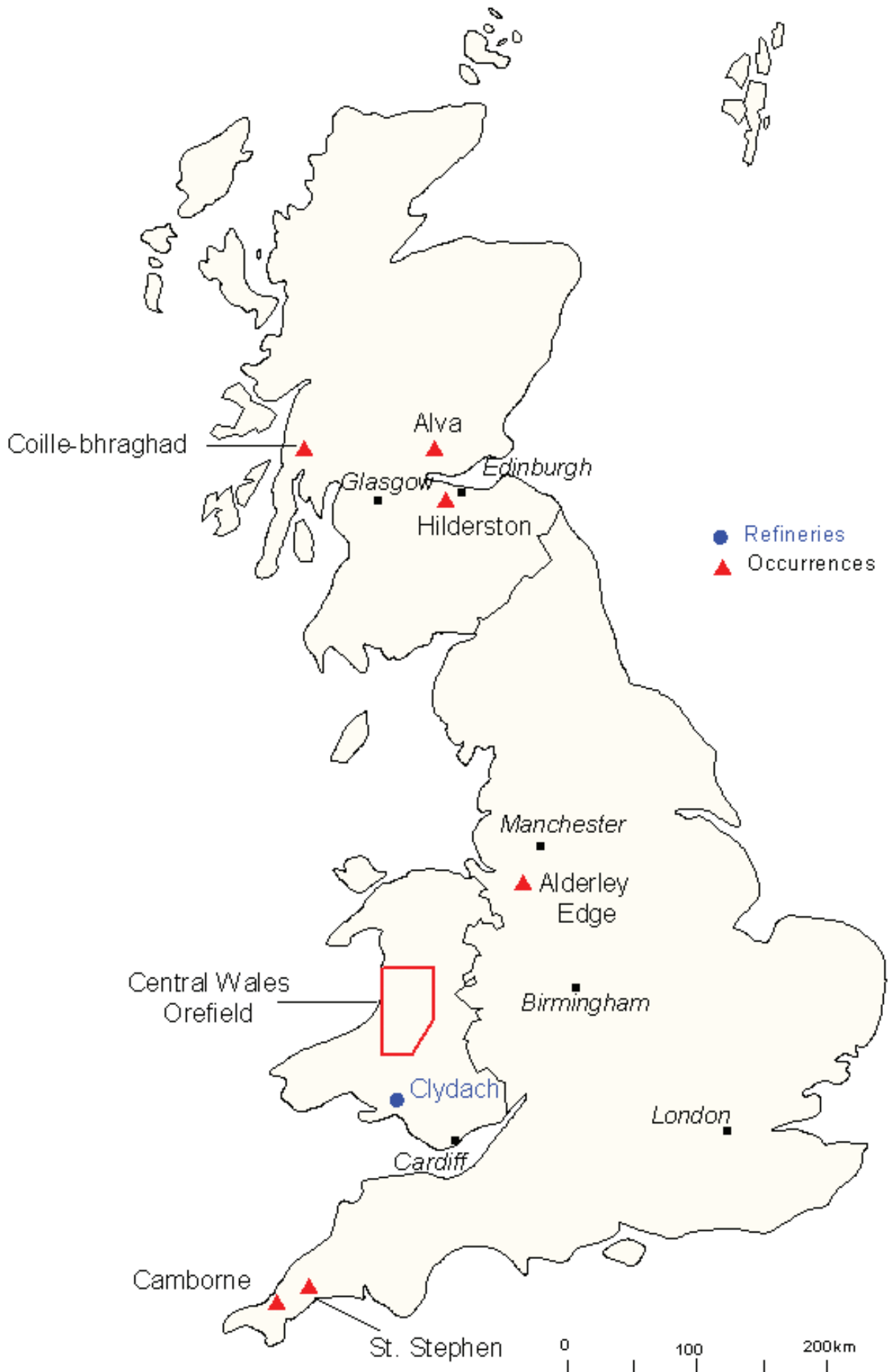


Figure 14 Location of principal cobalt occurrences and refineries in Britain.
(OS topography © Crown Copyright. All rights reserved. BGS 100017897/2009)

Further reading and selected references

Useful contacts for further information

Cobalt Development Institute	www.thecdi.com/
International Seabed Authority (for information of cobalt in nodules and crusts)	www.isa.org.jm/
First Quantum Minerals	www.first-quantum.com
Formation Capital Corporation	www.formcap.com/s/Home.asp
Geovic Mining Corporation	www.geovic.net/
Minerals Information Institute	www.mii.org/Minerals/photocobalt.html
Mining Journal Annual Review	www.mining-journal.com/reports
United States Geological Survey	minerals.usgs.gov

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