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Commodity Profile: Copper

Internal Report OR/09/041



BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT OR/09/041

Commodity Profile: Copper

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Native copper (Photo: P Lusty)

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This commodity profile provides an overview of copper, with up-to-date information on world production, trade and prices. Emphasis is placed on the British perspective. It is one of a series on important mineral commodities intended to inform a non-specialist audience.

Available from www.mineralsuk.com.

Definition, mineralogy and deposits

Definition and characteristics

Copper is a non-ferrous base-metal and its average concentration in the earth's crust is about 50 ppm (parts per million). The average minimum exploitable grade for a copper deposit is 0.4% which equates to a concentration factor of around 80 based on average crustal abundance. Copper occurs naturally in all plants and animals, as it is an essential element for all known living organisms.



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Figure 1 Native copper.

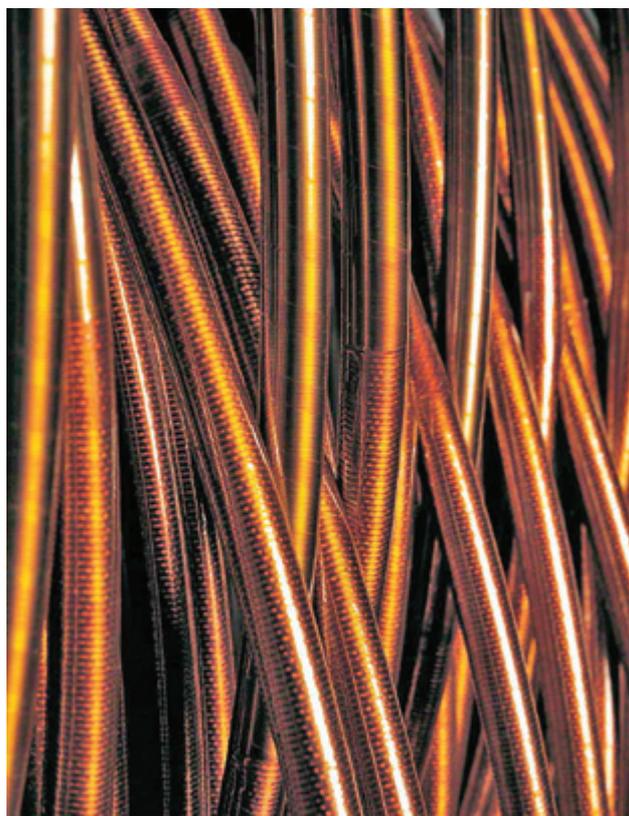
Copper is classified as a noble metal, like gold and silver, and as a result can be found in its elemental or 'native' form in nature (Figure 1). It is one of the transition metals in the periodic table which means it can also form compounds, such as chalcopyrite the main copper ore (CuFeS_2), and copper ions (Cu^+ or Cu^{2+}) in solution.

Copper metal has a characteristic reddish brown colour, with a metallic lustre on fresh surfaces. However, it quickly oxidises in air, a feature of all base-metals. Copper is relatively soft (2.5–3.0 on Moh's scale of hardness). Other physical properties are summarised in Table 1.

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Symbol	Cu	
Atomic number	29	
Atomic weight	63.546	
Density at 293 K	8960	kg/m ³
Melting point	1083	°C
Boiling point	2567	°C
Specific heat capacity at 293 K	386	J/kg
Electrical conductivity	100	% (International Annealed Copper Standard)
Electrical conductivity at 298 K	5.98×10^7	Ohm ⁻¹ m ⁻¹
Electrical resistivity	1.673×10^{-8}	Ohm m

Table 1 Properties of copper.



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Mineralogy

Copper combines with a number of elements and more than 150 copper minerals have been identified, although only a small number of these are of economic importance (Table 2). Copper minerals can be divided into three groups. Primary or hypogene¹ minerals related to hydrothermal² processes include bornite, chalcocite and enargite.

A second group are the copper oxides, typically formed from weathering of copper sulphides, that include cuprite, malachite, chrysocolla and covellite. The third group are secondary sulphides, such as chalcocite and covellite, formed from copper leached from near-surface sulphides.

Copper sulphide minerals contain a greater proportion of copper than oxides and disseminated sulphide deposits dominate global copper production. Estimates suggest at least 90% of copper is derived from sulphide deposits.

Mineral name	Chemical formula	Max. Cu content (wt%)
Native copper	Cu	100.0
Chalcocite	Cu ₂ S	79.9
Cuprite	Cu ₂ O	88.8
Covellite	CuS	66.4
Bornite	Cu ₅ FeS ₄	63.3
Malachite	Cu ₂ CO ₃ (OH) ₂	57.5
Azurite	2CuCO ₃ ·Cu(OH) ₂	55.3
Antlerite	Cu ₃ SO ₄ (OH) ₄	53.7
Enargite	Cu ₃ AsS ₄	49.0
Chrysocolla	CuSiO ₃ ·2H ₂ O	36.2
Chalcopyrite	CuFeS ₂	34.6

Table 2 Common copper minerals found in economic deposits.

Of the sulphide minerals, chalcopyrite is by far the most important accounting for approximately half of all copper production (Figure 2).

Deposits

Copper deposits are found worldwide in a variety of geological environments. Hydrothermal deposits are most significant on a global scale, although magmatic³ and supergene⁴ deposits are locally important (Table 3). Numerous other types of mineral deposits contain copper in variable amounts, however, these are of limited economic importance.



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Figure 2 Chalcopyrite, the primary ore of copper.

¹Hypogene: describes minerals formed within the earth by ascending fluids.

²Hydrothermal: hot fluids originating from igneous activity.

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

⁴Supergene: describes minerals formed within the Earth from descending fluids, such as percolating rainwater causing leaching.

Deposit type	Synonyms	Description	Examples
Porphyry		Large, relatively low-grade stockwork ⁵ to disseminated ⁶ deposits related to intrusions ⁷	Chuquicamata and La Escondida, Chile; Bingham Canyon, USA; Grasberg, Indonesia
Sediment-hosted	Shale-hosted copper, stratiform copper, Kupferschiefer-type, Central African type	Stratabound ⁸ disseminations of copper minerals occurring in a range of sedimentary ⁹ rocks	Nchanga, Zambia; Lubin, Poland; White Pine, USA
Red-bed	Sandstone-hosted, continental red-bed, basaltic copper, volcanic-hosted copper, copper mantos	Copper mineralisation occurring in oxidised zones in sedimentary (s) and volcanic ¹⁰ (v) rocks	Dzhezkazgan (s), Kazakhstan; Mantos Blancos (v), Chile
Volcanogenic massive sulphide (VMS)	Volcanic-associated, volcano-sedimentary-hosted massive sulphide deposits	Layered deposits hosted by submarine volcano-sedimentary sequences	Bathurst and Kidd Creek, Canada; Rio Tinto, Spain
Magmatic sulphide deposits		Sulphide concentrations associated with a variety of mafic ¹¹ and ultramafic ¹² magmatic rocks	Sudbury and Voisey's Bay, Canada; Noril'sk-Talnakh, Russia; Kambalda, Australia
Sedimentary exhalative (SEDEX)		Bodies of polymetallic sulphides deposited from hydrothermal fluids vented into sedimentary basins ¹³ with no obvious volcanic source	Broken Hill and McArthur River, Australia; Red Dog, Alaska
Epithermal		Veins, stockworks and breccias ¹⁴ associated with volcanic-related low-temperature hydrothermal systems	El Indio, Chile; Lepanto, Philippines; Monywa, Burma
Copper skarns	Contact metasomatic copper deposits	Mineralisation formed by chemical alteration associated with intrusions into carbonate rocks	Ok Tedi, Papua New Guinea; Copper Canyon, USA; Rosita, Nicaragua
Vein-style deposits	Polymetallic veins	Mineralised structures often developed along fractures varying from centimetres up to tens of metres wide from a variety of sources	El Indio, Chile; Copper Hills, Australia; Butte, USA
Supergene		In-situ natural secondary enrichment of primary mineralisation	Erdenet, Mongolia; La Escondida, Chile; Sarcheshmeh, Iran

Table 3 Summary of main copper deposit types.

⁵Stockwork: mass of many cross-cutting veins.

⁶Disseminated: small, fine-grained particles of ore mineral dispersed through a rock.

⁷Intrusion: a body of igneous rock emplaced into pre-existing rocks.

⁸Stratabound: an ore deposit that is confined to a single sedimentary bed or horizon.

⁹Sedimentary: rocks formed from material derived from other rocks by weathering.

¹⁰Volcanic: relating to volcanoes.

¹¹Mafic: dark coloured rocks containing iron- and magnesium-bearing minerals e.g. olivine.

¹²Ultramafic: dark coloured rocks containing almost entirely iron and magnesium-bearing minerals and virtually no felsic minerals such as quartz or feldspar.

¹³Sedimentary basin: a geologically depressed area containing sedimentary rocks.

¹⁴Breccia: a rock that has been mechanically, hydraulically or pneumatically broken into angular fragments.

Major deposit classes

Porphyry deposits

Porphyry copper deposits are currently the world's main source of copper (50–60% of world production), molybdenum (99% of world production) and rhenium¹⁵. They are also significant sources of gold, silver and tin and a range of by-product metals. Porphyry deposits are associated with subduction¹⁶-related felsic¹⁷ igneous¹⁸ intrusions. As a result they occur in plate boundary collision areas such as the Canadian Cordillera, the Andes Mountains and around the western margin of the Pacific Basin in the Philippines, Indonesia and Papua New Guinea.

The mineralisation is fracture-controlled, typically consisting of stockwork of quartz veins and breccias containing copper sulphides with gold and/or molybdenum. Mineralisation can develop in both the intrusive and host rock, typically associated with a core of intense alteration passing outwards into distinct zones characterised by other secondary alteration¹⁹ minerals. Mineralisation may occupy several cubic kilometres and deposits typically contain hundreds of millions of tonnes of ore, although they can range in size from tens of millions to billions of tonnes. Copper grades generally range from 0.2 per cent to more than 1 per cent.

Sediment-hosted deposits

Sediment-hosted deposits are the world's second most important source of copper accounting for approximately 20% of world production. They are also important sources of lead, zinc and silver and the world's primary source of cobalt, especially from the Central African Copperbelt. Deposits consist of disseminations of fine-grained sulphides in a variety of continental sedimentary rocks including black shale, sandstone and limestone. These sequences are typically associated with red-bed sandstones and evaporites²⁰.

Tonnages vary, with the average being 22 million tonnes grading 2.1% Cu and 23 g/t Ag (Mosier et al 1986) but can be as much as several hundred million tonnes. The enormous Lubin orebody in south-west Poland contains

2600 million tonnes with >2.0% Cu and 30–80 g/t Ag. The Central African Copperbelt is the world's largest province containing stratiform²¹ sediment-hosted copper mineralisation. The Copperbelt is a 600 kilometre long and 50 kilometre wide belt extending across Zambia and the Democratic Republic of Congo.

Boundaries between different base-metal deposit types in sedimentary/volcanic sequences are sometimes unclear and depend heavily on the selection criteria employed.

Red-bed copper deposits

The two types of red-bed mineralisation are volcanic and sedimentary. Volcanic-hosted deposits occur in mafic terrestrial lava flows and associated volcanoclastic sedimentary rocks with sulphides disseminated through permeable²² host rocks or filling cavities.

Sedimentary-hosted deposits form in red continental sediments deposited in oxidising environments and consist of disseminated sulphide deposited in permeable layers in the host rock. It is suggested that copper is precipitated in these deposits when oxygen-rich fluids rise through permeable zones and encounter reduced material such as organic matter and pyrite.

Sedimentary-hosted deposits are generally uneconomic due to their small size, although they have been worked at Dzhezkazaga, Kazakhstan and Paoli, USA. In contrast, volcanic-hosted deposits are important copper producers. Tonnages range from hundreds of thousands to hundreds of millions of tonnes, typically grading around one to four percent copper.

Volcanogenic massive sulphide (VMS) deposits

VMS deposits are important sources of copper and many other metals owing to their widespread distribution, substantial tonnages (0.1–500 million tonnes) and relatively high grades. Precious metals, including silver and gold, are common by-products. Ore bodies are large, stratiform lenses and sheets formed on the seafloor through the discharge of metal-rich hydrothermal fluids.

¹⁵Rhenium: a rare, heavy, silvery-white metal used in alloys.

¹⁶Subduction: the movement of oceanic crust under continental crust.

¹⁷Felsic: rock containing light coloured silicate minerals e.g. quartz and feldspar.

¹⁸Igneous: rocks which have a crystalline texture and appear to have consolidated from molten rock.

¹⁹Alteration: changes in the chemical or mineral composition of a rock.

²⁰Evaporite: a sedimentary rock composed of minerals produced by evaporation of water e.g. gypsum and rock salt.

²¹Stratiform: an ore deposit that occurs as a specific sedimentary bed.

²²Permeable: allows a gas or fluid to move through it.

They are formed in extensional tectonic²³ settings with modern-day examples currently developing at spreading centres²⁴ and in oceanic arc²⁵ terranes. A mound-shaped, stratabound massive sulphide body is typically underlain by a stockwork feeder zone. Deposits are generally restricted to specific stratigraphic²⁶ intervals within a province and tend to occur in clusters.

VMS deposits may be divided into three main categories based on their mineralogy — Kuroko, Besshi and Cyprus types. Deposits vary in size considerably but are generally high grade and low tonnage, with some giants such as Rio Tinto, Spain with around 250 million tonnes at 1% Cu, 2% Zn and 1% Pb (Galley et al.).

Magmatic sulphide deposits

A diverse group of deposits containing copper in association with nickel and platinum-group elements (PGE) occurring as sulphide concentrations within mafic and ultramafic rocks.

As a magma²⁷ rises through the crust it cools and, if the sulphur content of the magma is sufficient, a separate liquid sulphide phase may develop (droplets of sulphide liquid in a silicate liquid). Elements such as nickel, copper, PGE and iron preferentially transfer into the sulphide phase from the surrounding magma. The metal-rich sulphide liquid tends to sink because of its greater density, forming sulphide concentrations on the magma chamber²⁸ floor.

Worldwide deposits typically grade between 0.2 and 2% Cu with ore tonnages ranging from a few hundred thousand to tens of millions of tonnes. The largest magmatic sulphide nickel-copper deposits are of Archean (4000–2500 million years) and Proterozoic (2500–540 million years) age and are found at Sudbury, Ontario and Noril'sk-Talnakh, Russia.

Sedimentary exhalative deposits (SEDEX)

These deposits are important sources of lead, zinc and silver. Copper may be a significant by-product. SEDEX, an acronym for 'sedimentary exhalative', are deposits

formed by the exhalation of brines²⁹ into seawater, causing chemical precipitation of minerals as the brine cools.

SEDEX deposits display many similarities to VMS deposits, except for the close volcanic association and are interpreted as forming further from the exhalative source. Deposits are typically represented by sheet or tabular lenses consisting of bands of fine-grained sulphide intercalated with shale, silt and carbonate host rocks. The sulphide bodies generally only measure a few metres thick but may extend laterally for more than a kilometre. The median tonnage for global deposits is 15 million tonnes with grades of 5.6% Zn, 2.8% Pb and 30 g/t Ag (Briskey, 1986). Deposits may contain up to one percent copper. Broken Hill, McArthur River and Mount Isa in Australia; Meggen and Rammelsberg in Germany and Tynagh in Ireland are all SEDEX deposits containing copper as a significant by-product.

Epithermal deposits

Epithermal deposits are most significant for their gold production but may contain significant quantities of silver, copper and other metals. Deposits are associated with subduction-related environments at plate boundaries. These deposits may take the form of veins, stockworks or breccias and are mainly Tertiary (63–2 million years) to Quaternary (2 million years to present) in age. They usually form at shallow crustal levels (300–600 m) by circulation of magmatic fluids through volcanic rocks. Deposits are often spatially related to porphyry deposits. Principal ore minerals include chalcocite, covellite, bornite and native gold with minor amounts of chalcopyrite. There is considerable variation in grade and tonnage of these deposits but they can be extremely rich e.g. El Indio, Chile with grades up to 178 g/t Au, 109 g/t Ag and 3.87% Cu (Panteleyev, 1996).

Skarn deposits

A skarn is a metamorphic³⁰ rock that forms as a result of chemical alteration by hydrothermal and other fluids. Copper skarns most frequently develop where granite³¹ intrusions are emplaced into continental margin³² carbonate sequences, such as limestone or dolomite, causing intense alteration and mineral replacement.

²³Extensional tectonics: the tectonic processes associated with, the stretching of the Earth's crust.

²⁴Spreading centres: a region where two plates are being pulled apart and new crust is formed as molten rock is forced upward into the space e.g. Mid-Atlantic Ridge.

²⁵Oceanic arc: a chain of volcanic islands produced as one plate moves under another and melts.

²⁶Stratigraphic: the spatial ordering of geological layers or strata.

²⁷Magma: molten rock.

²⁸Magma chamber: a space below ground filled with magma.

²⁹Brine: water saturated or close to saturation with salt.

³⁰Metamorphic: rocks changed by temperature and pressure within the Earth's crust.

³¹Granite: an intrusive rock dominated by quartz and feldspar.

³²Continental margin: the zone of transition from a continent to ocean basin.

Deposits are highly varied in form ranging from tabular lenses to vertical pipes with irregular ore³³ zones controlled by the intrusive contact³⁴. The largest copper skarns are associated with porphyry copper deposits. Copper mineralisation is present as stockwork veining and disseminations in both the intrusive and the surrounding host rock. Chalcopyrite tends to be the dominant copper mineral, occurring with bornite and tennanite³⁵. Globally, copper skarns average one to two percent copper, generally ranging from one to hundred million tonnes, although some exceptional deposits exceed 300 million tonnes. Major copper skarn mineralisation is associated with the Ok Tedi porphyry intrusive system in Papua New Guinea.

Vein deposits

Vein deposits are intimately associated with many of the deposit classes discussed above. Veins are mineralised structures typically developed along fractures and varying in thickness from centimetres to tens of metres or more. Sulphides are commonly irregularly distributed as patches and disseminations within quartz, carbonate and other gangue³⁶ minerals.

The importance of vein deposits has steadily diminished as changing economics and improved extraction techniques have allowed large, low-grade deposits to be mined. Copper commonly occurs in veins associated with quartz, silver, gold and occasionally uranium, antimony and phosphorus. These polymetallic³⁷ veins may be related to porphyry copper, copper skarn, epithermal gold-silver-copper and sediment-hosted copper deposits. At the El Indio mine in Chile massive sulphide veins can be over 10 m thick with average grades of 2.4% Cu (Evans, 1993).

Supergene deposits

Secondary enrichment can affect most classes of mineral deposit. Supergene³⁸ alteration is in-situ secondary enrichment of a deposit whereby the primary ore minerals are oxidised, dissolved and reprecipitated by reduction, commonly at the water table³⁹. Supergene enrichment takes place above the primary hypogene ore and can be laterally and vertically extensive (reaching tens of metres

downwards). This is an important process as it can affect the economics of mining, especially of low-grade porphyry and VMS deposits.

Enrichment blankets containing high-grade copper minerals, such as chalcocite, covellite and bornite, may enhance the average grade of the ore to one to three percent copper. Supergene enrichment favours rocks that are permeable to meteoric water and contain abundant pyrite to allow the formation of oxidising acids. The presence of acid-soluble metal-bearing minerals and a redox barrier⁴⁰ (such as the water table) at depth may also contribute to the formation of supergene deposits.

Supergene enrichment has been a major factor in the development of several porphyry copper deposits. At La Escondida, in Chile, the supergene blanket constitutes around 65% of the copper resource of the deposit. Grades of up to 3.5% Cu are recorded in this zone. A leached cap containing lower grades of copper and molybdenum overlies the enriched sulphides.

Deposit styles – implications for exploitation

The large size of porphyry copper deposits, their relatively low-grade and the intimate association of fractured host rock, alteration and mineralisation makes them amenable to open-pit mining methods. With relatively thin horizons such as those found in sediment-hosted copper deposits, higher grades are required as they are typically mined using underground methods. In addition, the polymetallic nature and broad lateral extent of these deposits make them attractive. VMS deposits are sometimes viewed as less favourable targets for mining companies when compared to porphyry and sediment-hosted copper deposits as a result of their complex mineralogy and shape. However, due to their polymetallic nature, VMS deposits are advantageous during periods of fluctuating metal prices. The shallow depth of formation of epithermal deposits generally allows the use of bulk open-pit mining methods, although some higher grade deposits are selectively worked underground.

³³Ore: rock from which metal or minerals can be extracted.

³⁴Intrusive contact: the zone between an intrusion and the surrounding host rock.

³⁵Tennanite: a copper-iron-arsenic sulphide mineral.

³⁶Gangue: the undesirable or unwanted minerals in an ore deposit.

³⁷Polymetallic: comprised of a combination of metals.

³⁸Supergene: ore minerals formed by processes commonly involving water containing dissolved material descending from the surface.

³⁹Water table: underground surface below which the ground is completely saturated.

⁴⁰Redox barrier: the zone at which oxidation-reduction reactions occur.

Extraction methods and processing

Extraction

Copper ore is extracted using three principle techniques. The technique applied depends on the characteristics and geographic location of the ore body (Figure 3).

Open-pit mining

This is the most common form of copper ore production. It is generally appropriate for near-surface (<100 m), lower grade steeply dipping or massive ore bodies such as porphyry copper, copper skarn, SEDEX and most epithermal deposits all of which are generally amenable to bulk extraction.

The ore is extracted by digging or blasting with explosives. It is then loaded onto trucks or conveyors and hauled to a stockpile prior to further processing. The open pit copper mine at Bingham Canyon, Utah, USA, is one of the largest man-made excavations in the world. It is over 800 m deep and four kilometres wide. It has been in operation over 100 years, mining chalcopyrite with minor bornite. Bingham Canyon has cumulatively produced more copper than any other mine in history, approximately 15 million tonnes.

Underground mining

Before the 1900s, copper was produced almost exclusively from underground mines. Today, underground production is less common due to the higher costs and safety issues.

Underground mining is suitable to extract higher grade, small or deep ore bodies. Techniques used include block caving (for large, uniform deposits), room and pillar (typically for flat, <30° dipping deposits), and a variety of stoping methods (for narrow or steeply dipping veins). The Lubin mine, in the Legnica-Glogow Copper district of Poland, uses the room and pillar method of mining and currently has about 20 km² of tunnels.

In-situ leaching

A system of injection and recovery wells completed from the surface or from underground workings can be used to extract copper from relatively deep, low-grade ore bodies with minimal surface disturbance. The process requires the deposit to be permeable and the surrounding rock impervious⁴¹. A weak sulphuric acid leach solution is pumped down injection wells and into the ore body. Copper is dissolved into the solution as the leachate flows

through the deposit. This copper-rich solution is pumped out through recovery wells which surround the injection well and prevent the leaching solution from escaping. On completion, fresh water is pumped around the system for cleaning and the wells are cemented. In the Mopani mines on the Zambian Copperbelt, in-situ leaching is being conducted from old underground workings.

Processing

Ore grades and mineral composition will vary depending on the type of mineralisation. Mined ores generally contain 0.5%–3% Cu. The first phase in processing the ore is concentration which increases the copper content to 25%–35%. This is typically carried out at the mine site and involves crushing and grinding, followed by chemical and/or physical processing and separation stages. Once the copper has been concentrated it can be converted into pure copper metal using two techniques:

1. Pyrometallurgical processes, including smelting and electrolytic refining.
2. Hydrometallurgical processes, including leaching, solvent extraction and electro-winning (SX-EW).

The two processes run well in parallel because during smelting pyrometallurgy produces sulphur dioxide gas, which can be converted into sulphuric acid and hydrometallurgy consumes large quantities of sulphuric acid for leaching.

Currently, hydrometallurgy is primarily used only for oxide ores. However, research into commercially feasible extraction of copper from primary sulphides which can compete against smelting techniques is ongoing. Hydrometallurgical processes have many advantages over pyrometallurgical processes including:

- lower grade ore can be processed;
- higher energy efficiency because lower temperatures are required, (although large amounts of electricity are required in the electrowinning phase);
- lower environmental impact because waste streams are liquid and more easily contained and neutralised than, for example, the sulphur dioxide gas which is emitted during smelting;
- lower capital and operational costs make hydrometallurgy more economical for smaller scale operations.

⁴¹Impervious: incapable of being penetrated by gas or liquid.

Copper

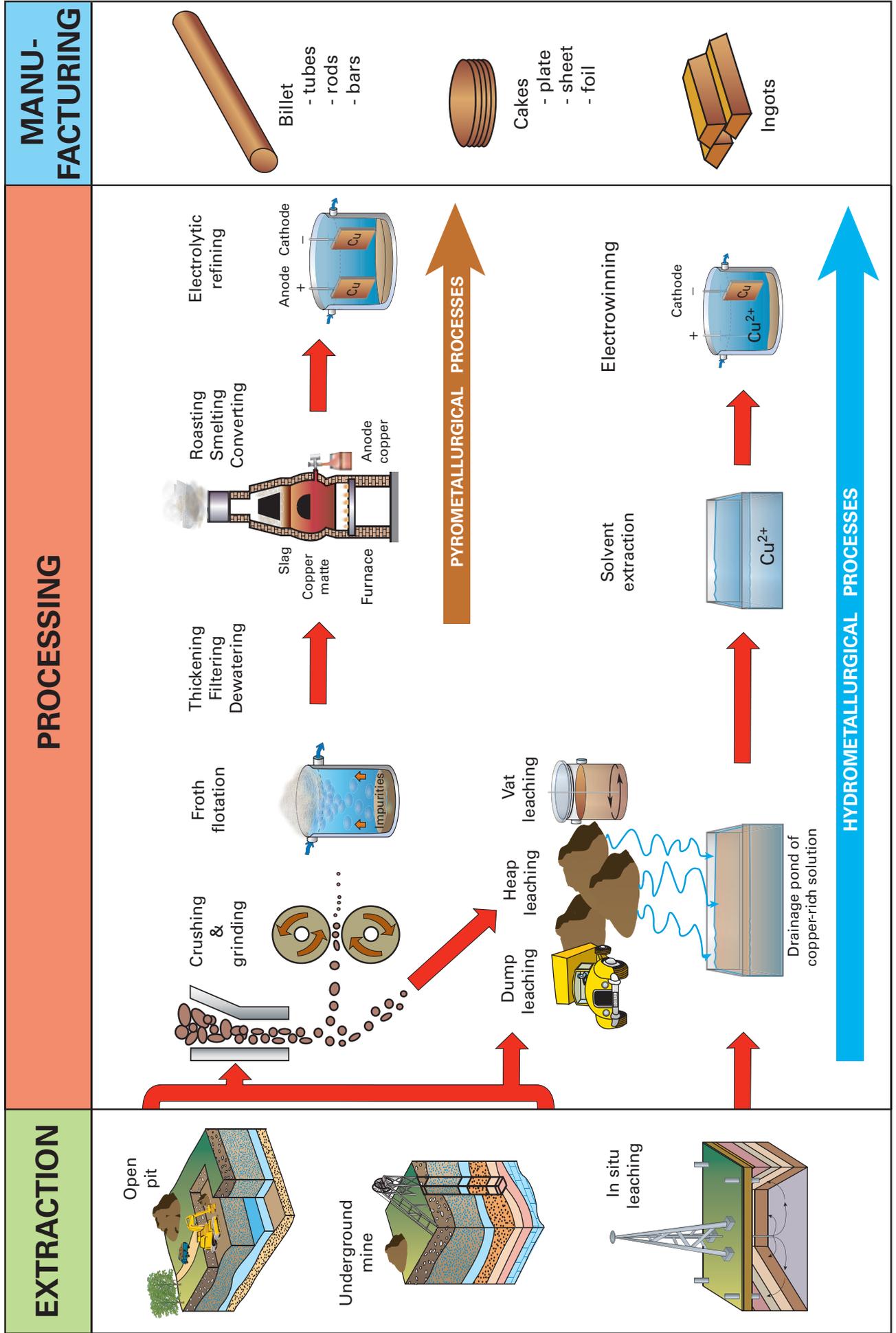


Figure 3 Copper processing from extraction to manufacture.

Suitable ore beneficiation methods are chosen and often adapted to suit the specific mineralogical characteristics and geographic location of the ore body. Important factors range from the composition and texture of the ore and gangue minerals present, to the availability of labour, water and electricity.

Concentration

Crushing and grinding

The ore is fed into a primary crusher, followed by one or more stages of secondary crushing. At each stage vibrating screens allow material with the desired dimensions to pass on to the next part of the processing circuit. Following crushing, the ore is mixed with water to create a slurry. This is fed into a series of grinders until a powder of the required grain size is produced.

Froth flotation

Froth flotation is a selective process for separating minerals using water, various chemicals and compressed air.

Following grinding, additional water is added to the powdered ore to produce a suspension. Chemicals are added, making certain minerals water repellent and causing air bubbles to stick to their surfaces. Consequently, these minerals collect in a froth at the surface and are removed. The resulting concentrate is dewatered in thickeners and filters and contains approximately 25–35% Cu, 25% S and 25% Fe, with varying quantities of other impurities.

Leaching

Leaching is another method that may be used to concentrate the copper ore which can be employed either before or after the crushing stage. This process is covered in more detail under 'Hydrometallurgical processes'.

Pyrometallurgical processes

The copper concentrate is fed into a smelting furnace to further separate the copper from impurities. Recyclable scrap copper may also enter the process. Four stages are involved: roasting, smelting, converting and fire refining. Some smelters combine some of these into a continuous process. Matte copper (35–68% Cu) is first produced, followed by blister copper (97–99% Cu). Blister copper can be further purified to anode copper (99.5% Cu) by fire refining or cathode copper by electrolytic refining (99.95–99.96% Cu).

Roasting

Roasting converts the copper concentrates to oxides, removing most of the sulphur as sulphur dioxide gas, which can be captured and converted to sulphuric acid (H_2SO_4). Other impurities, such as antimony, arsenic, and lead are also driven off. The concentrate is mixed with a siliceous flux⁴² and heated to about 650°C.

Smelting

The dry, hot roasted ore concentrate together with siliceous flux is charged into the smelter, which is maintained at 1000–1500°C. Impurities are removed from the molten roasted concentrate by oxidation, leading to the segregation of a slag⁴³ which is skimmed off and discarded. Matte is the molten mixture under the slag, comprising copper sulphide, iron sulphide and some heavy metals (35–68% Cu), which remains to be converted to pure metal.

Converting

Air is blown through the molten matte to oxidise the iron and copper sulphides. This produces more sulphur dioxide, which can be captured to make acid. A silica and lime flux is added which combines with the iron to form slag, leaving blister copper (97–99% Cu).

Fire refining

Blister copper is mixed with flux and enters the anode furnace, which is maintained at 1100°C. Air is blown through the molten mixture to oxidise the copper and any remaining impurities. The impurities are removed as slag. The remaining copper oxide is then subjected to a reducing atmosphere to form purer copper, which is cast into anodes (99.5% Cu). This can now be used in some alloys or castings but for the majority of applications, further purification by electrolytic refining is necessary.

Electrolytic refining

The anodes cast during the fire refining stage are immersed in a sulphuric acid bath. The anode⁴⁴ dissolves and copper ions move through the solution to the cathode where they are deposited on 'starter sheets' of stainless steel or pure copper foil (Figure 4). The impurities precipitate out and collect at the bottom of the bath as sludge which can be recycled to extract other metals such as gold, silver and platinum. The cathodes are removed after one to two weeks, with 50–150 kg copper deposited on each side of the original starter sheet.

⁴²Flux: material added to a furnace to remove impurities and make the slag more liquid.

⁴³Slag: waste material, which floats to the top during a smelting operation.

⁴⁴Anode: the positive electrode in an electrochemical cell.

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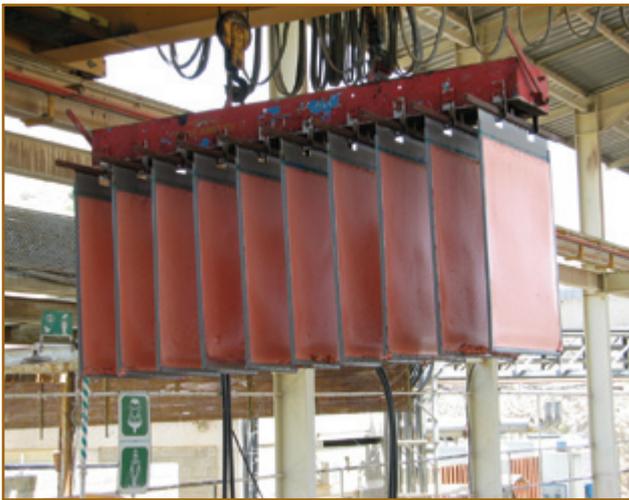


Figure 4 Copper cathodes.

Hydrometallurgical processes

Hydrometallurgical processing involves chemical or biological leaching of copper from the ore using dilute sulphuric acid. The weak solution is concentrated using solvent extraction techniques (SX) and the copper is precipitated out by electrowinning (EW). In some circumstances, copper is precipitated out of the leached weak solution, before the concentration stage, by pouring it over scrap iron to form 'cement copper'. Here the copper precipitates out onto the iron and has to be scraped/raked off daily. This is only seventy to eighty percent pure and must then be smelted and refined.

Leaching

Copper oxide ore, low-grade copper sulphide ore or mine waste (tailings) are placed in heaps or vats (Table 4). Weak sulphuric acid is trickled through the heap to dissolve the copper minerals. Chemicals such as ferric chlorides can be added to help enhance dissolution of copper sulphides. Particular strains of bacteria can be injected into the heap to accelerate the process, in a technique known as bio-leaching. Increasing pressure and temperature in vat leaching can also facilitate dissolution. Leaching produces a solution with a concentration of thirty to seventy percent copper which is recovered from drainage tunnels and ponds.

The highest and fastest yields of copper can be extracted from oxide ores, or those which do not contain iron. Yields may reach 50% in a year and 90% in five years using the heap leach technique. Yield times can be as short as days or months for vat leaching.

Sulphide ores generally take much longer to leach and produce a much lower yield (10–15% per year is typical in the early stages). Research is underway to find faster

methods of extracting copper from sulphide ores using leaching.

Solvent extraction (SX)

The solution recovered from leaching is mixed with a chemical called an extractant, which selectively removes the copper from the original acidic solution leaving behind most of the impurities. A fresh acidic solution is used to strip the copper from the extractant. The resulting, highly concentrated copper solution is called a pregnant liquor solution (PLS) which is transferred to the final stage of electrowinning.

Electrowinning (EW)

The copper-rich solution is filtered, heated, then passed through a series of electrolytic cells. A much larger voltage is applied to the cells (3V) compared to electrolytic refining (0.2V), because the copper has to first be reduced from copper sulphate in solution to copper metal. The copper precipitates out onto stainless steel starter sheets to form high-purity cathodes (99.99% Cu) and the acid is recycled.

Type	Suitable for	Preparation / Method	Timescale to extract ~70% Cu
Dump	Large volumes of low-grade ore and waste	No preparation	Months to years
Heap	Low-grade ores	Crushed and ground	Days to months
Vat	Relatively low volumes, generally higher grade ore	Crushed/ground oxides agitated in percolating tanks	Hours or days

Table 4 Processing and timescales for different leaching methods for copper oxide ores.

Copper manufacture

The copper cathodes produced from electrolytic refining and electrowinning are shipped to mills and foundries where they are cast into wire rod (for wires), billets (to make tubes, rods and bars stock), cakes (to make plate, sheets and foil) or ingots (for alloying or casting). These copper and copper-alloyed products are then shipped for final manufacturing, or distribution, to meet consumers needs. Scrap (including excess material discarded during manufacturing and copper-bearing products sent for disposal) can be recycled back into the system.

Specification and uses

Specification

Copper is used and traded in a wide variety of forms, the most important of which are discussed below.

Copper matte a mixture of copper and iron sulphides in the form of black granules or consolidated mass. The majority of matte never enters the market and is refined to a purer form.

Cement copper a fine black powder containing oxides and insoluble impurities precipitated by adding iron to a copper leachate solution or by pouring over scrap iron.

Black copper an impure form of copper produced by smelting oxidised copper ores of impure scrap. Copper content is typically in the range of 60–85%.

Blister copper an impure form of copper produced by blowing air through molten copper matte. The copper content is generally around 98%.

Copper anodes are slabs produced from further refining. Hot air is blown through the copper at a higher temperature than for blister copper. It is then subjected to a reducing atmosphere. The cast slabs are used as copper anodes in electrolytic refining.

Refined copper is metal containing at least 97.5% by weight copper. Refined copper is fabricated to produce finished products of various shapes according to intended end-use. These include bar, rod, tube, sheet, plate, foil, strip, castings, and powder.

Copper alloys are mixtures of metals in which copper is the dominant metal by weight. The precise combination of elements to form an alloy is usually designed to take advantage of and enhance certain characteristics for a specific purpose. For example, copper is mixed with tin to form bronze which has superior hardness and strength than copper alone. There are over 370 commercial types of copper alloys in use today. These can take the form of cast⁴⁵ or wrought⁴⁶ alloys.

Copper compounds various copper-bearing compounds are used in commercial applications. Copper sulphate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), a characteristically bright blue salt, is the most important and widely used copper compound. Other

important copper compounds include copper acetates, cupric oxide, chloride and nitrate, cuprous chloride, copper cyanide, copper naphthenate and copper soaps.

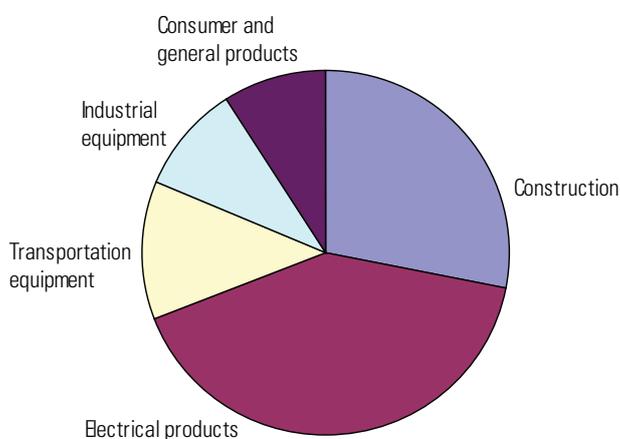
Uses

The ability to conduct electricity and heat are two of the most important properties of copper, since about a quarter of all copper produced is used in electrical applications (Figure 5).

Copper's excellent resistance to corrosion and long life span is illustrated by its extensive use in architecture, particularly roofing, where it can survive for more than a hundred years. When alloyed with other metals it acquires additional properties including increased hardness, tensile strength and improved corrosion resistance. Brass and bronze are two of the most important alloys of copper. Its malleability and ease of use in machines during the fabrication process allows for a high production rate of accurate copper shapes for a relatively lower cost than that of its substitutes. As a result of these and other important properties discussed below, copper has become a major industrial metal, ranking third after iron and aluminium in terms of quantity consumed.

Construction

Copper's largest use is in construction, which is dominated by building for residential purposes. Copper is used in many forms in buildings including wire, plumbing pipes and fittings, electrical outlets, switches and locks. Construction of an average modern house requires at least 200 kg of copper metal. Copper roofing is highly rated for its corrosion resistance and architectural characteristics.



Figures 5 Consumption of copper by end-use sector. Source: ICSG.

⁴⁵Cast: metal shaped in casting moulds when molten.

⁴⁶Wrought: metal cut, shaped or worked when solid.

Electrical

Copper is the best electrical conductor after silver and is widely used in the production of energy-efficient power circuits. Electron tubes used in televisions and computer monitors, audio and video amplification and in microwave ovens depend on copper for their internal components. Copper is extensively used in computers where cables, connectors and circuit boards all rely on copper. Copper is increasingly being used in computer chips in place of aluminium, resulting in faster operating speeds. Copper wire is extensively used in telecommunications and is essential for high-speed communication between computers.

Consumer and general products

Copper is extensively used in household products. Most silver-plated cutlery has a copper-zinc-nickel alloy base. Copper is used in many other domestic applications including cooking pans, lighting, clocks and for decorative purposes.

Transportation

Copper is commonly used for radiators, brakes and wiring in motor vehicles, with a modern car containing up to 28 kg of copper. Improvements in electronics and addition of powered accessories have led to increased use of copper in modern cars. Copper-nickel alloys are biotoxic and help reduce the growth of organisms on the hulls of ships and boats.

World resources and production

World resources

According to USGS world identified resources of copper are estimated at about 1.6 billion tonnes, not including about an additional 700 million tonnes in deep-sea nodules. Current world reserves are estimated at 467 000 tonnes, nearly one third of which are found in Chile (Table 5).

Country	Reserves (tonnes)	Percent share
Chile	140 000	30.0
United States	35 000	7.5
Indonesia	35 000	7.5
Peru	30 000	6.4
Poland	30 000	6.4
Mexico	27 000	5.8
China	26 000	5.6
Australia	24 000	5.1
Russia	20 000	4.3
Zambia	19 000	4.1
Kazakhstan	14 000	3.0
Canada	7 000	1.5
Rest of the world	60 000	12.8

Table 5 World copper metal reserves 2005. Source: USGS.

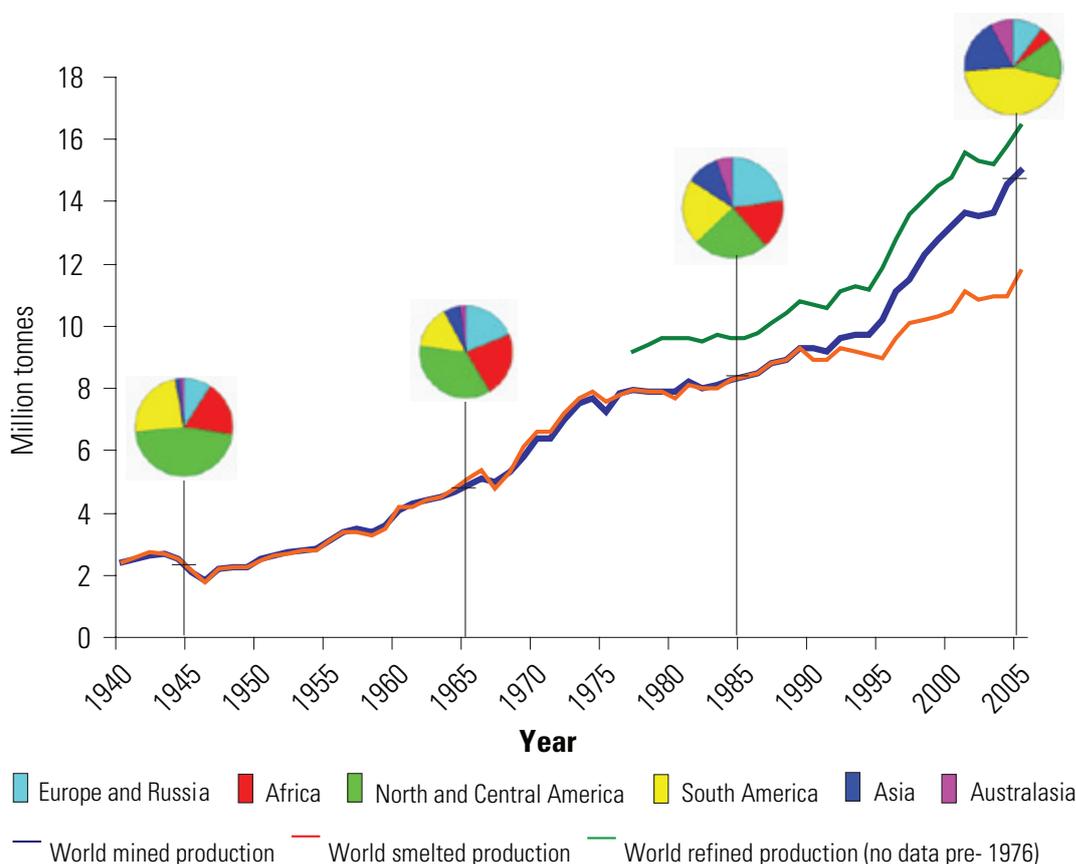


Figure 6 World production of mined, smelted and refined copper 1940 – 2005. Pie charts show percentage mined in each region.

World production

Copper is produced in around fifty countries, six of which currently mine over 500 000 tonnes of copper each annually. The total production from these six countries amounts to 80% of world mine production.

During the last 65 years global mined production of copper has increased at an average rate of 2.6% per year (Figure 6). In the last 20 years, copper production has almost doubled from 8.4 million tonnes in 1985 to 15 million tonnes in 2005. This sustained rise in copper production can be attributed to the steady rise in copper demand from growing economies around the world.

The proportion of copper mined in South America has increased from about one quarter to nearly one half of total world production (Figure 7). This is largely due to an increase in production from Chile, from 16% of world production in 1985, up to 35% in 2005. A more stable political climate has created favourable conditions for mining companies to tap Chile's vast copper resources. In North and Central America production has declined and the contribution from Asia has been increasing. During the last 10–15 years mine production has become decoupled from total smelter production, whereas prior to 1990 the two correlated very well. This divergence can be explained by increasing use of hydrometallurgical extraction techniques which compete with smelter production.

Rising demand for copper means that many mines are now operating at almost full capacity (about 90% capacity in 2005 according to the International Copper Study Group ICSG). Smelting and refining are also reaching a bottleneck. This, coupled with limited expansion potential and diminishing ore reserves of existing mines, means that production is likely to level off unless the currently high copper prices are reinvested into exploration and future production infrastructure. Mined copper production is vulnerable to disruptions in supply caused by problems such as strikes, natural disasters and concerns over supplies of natural gas and water. Water is of particular relevance in Chile, where mines high in the Atacama Desert compete for water with growing cities.

Improved mining and extraction techniques now allow copper from lower grade ores that were previously considered as waste to be extracted using chemical and bio-leaching

techniques. However, in many cases the leach cycle may be measured in years, resulting in a considerable lag time in copper metal production by these methods.

Total world production in 2005 was 15 million tonnes (Table 6). Chile is the largest copper producing country (Figure 7). In 2005 Chile mined 5.3 million tonnes of copper, 35% of world production. The two largest producing mines in 2005 were La Escondida and Chuquibambilla in Chile (Table 7).

Total world production of smelter copper was 11.9 million tonnes in 2005 (Table 8 and Figure 8). There are over 100 smelters in operation in more than 30 countries, with Asia contributing 44% of the world total production in 2005.

	Total (tonnes)	% of world
Asia	2 839 246	19
N & C America	2 163 854	14
Europe	1 549 157	10
S America	6 650 643	44
Africa	684 538	5
Australasia	1 122 978	7
	15 010 416	

Table 6 2005 mine production of copper.

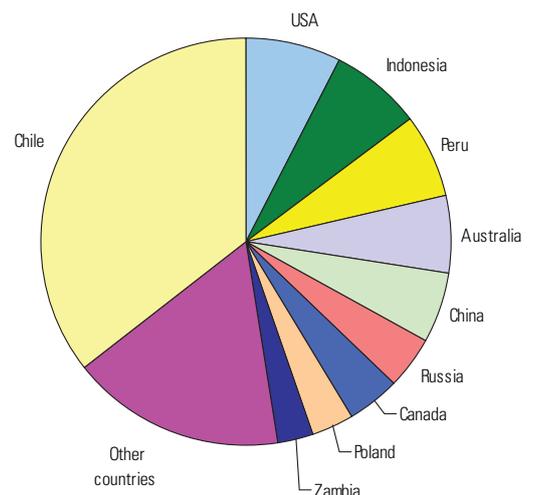


Figure 7 2005 mine production of copper. Source: BGS World Mineral Production 2001–2005.

Ranking	Mine	Country	Main owner	Production 2005 (to nearest 100 tonnes)	% of world
1	La Escondida	Chile	BHP Billiton	1 157 400	7.7
2	Coldeco Norte (Chuquicamata)	Chile	Coldeco	964 900	6.4
3	Grasberg	Indonesia	Freeport McMoran	662 200	4.4
4	El Teniente	Chile	Coldeco	437 400	2.9
5	Collahuasi	Chile	Anglo American	427 100	2.8
6	Morenci	USA	Phelps Dodge	400 000	2.7
7	Antamina	Peru	BHP Billiton /Xstrata	364 700	2.4
8	Los Pelambres	Chile	Antofagasta	322 800	2.1
9	Batu Hijau	Indonesia	Newmont	270 300	1.8
10	Andina	Chile	Coldeco	248 100	1.7

Table 7 Top 10 copper mines, based on 2005 mine production.

Total world refined copper production was 16.6 million tonnes in 2005, from over 40 countries (Figure 9). In 2005 38% of refined copper was produced in Asia (Table 9).

The majority of mines shown in Table 7 are open pit, although Grasberg in Indonesia has both open pit and underground operations (Figure 10). Production from Grasberg's Deep Ore Zone (DOZ) is by a block cave operation which is one of the world's largest underground mines. Nineteen percent of mill throughput per day is from the DOZ.

	Totals (tonnes)	% of world
Asia	5 304 000	31
N & C America	1 305 000	8
Europe	2 384 000	14
S America	2 079 000	12
Africa	382 000	2
Australasia	412 000	2
	11 866 000	

Table 8 2005 smelter production of copper.

	Total (tonnes)	% of world
Asia	6 309 000	38
N & C America	2 149 000	13
Europe	3 549 000	21
S America	3 549 000	21
Africa	557 000	3
Australasia	471 000	3
	16 584 000	100

Table 9 2005 refined production of copper.

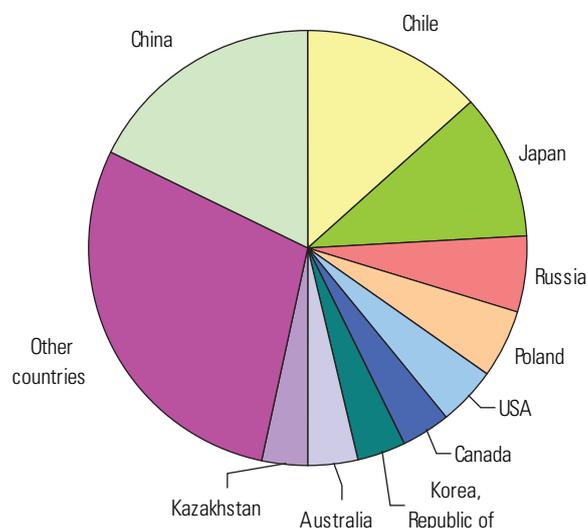


Figure 8 2005 smelter production of copper.
Source: BGS World Mineral Production 2001–2005.

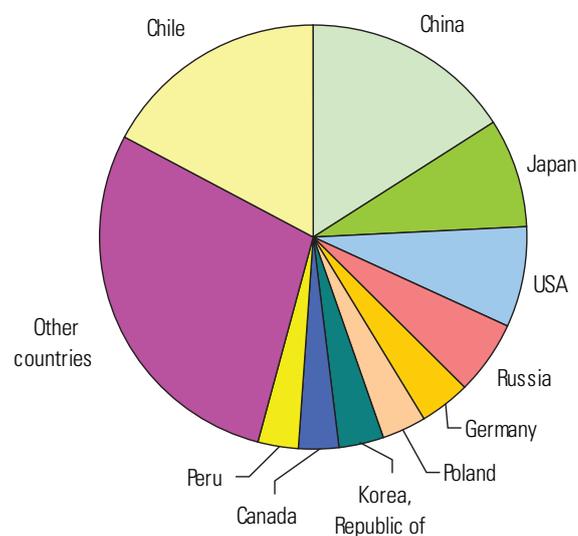


Figure 9 2005 refined production of copper.
Source: BGS World Mineral Production 2001–2005.

Copper

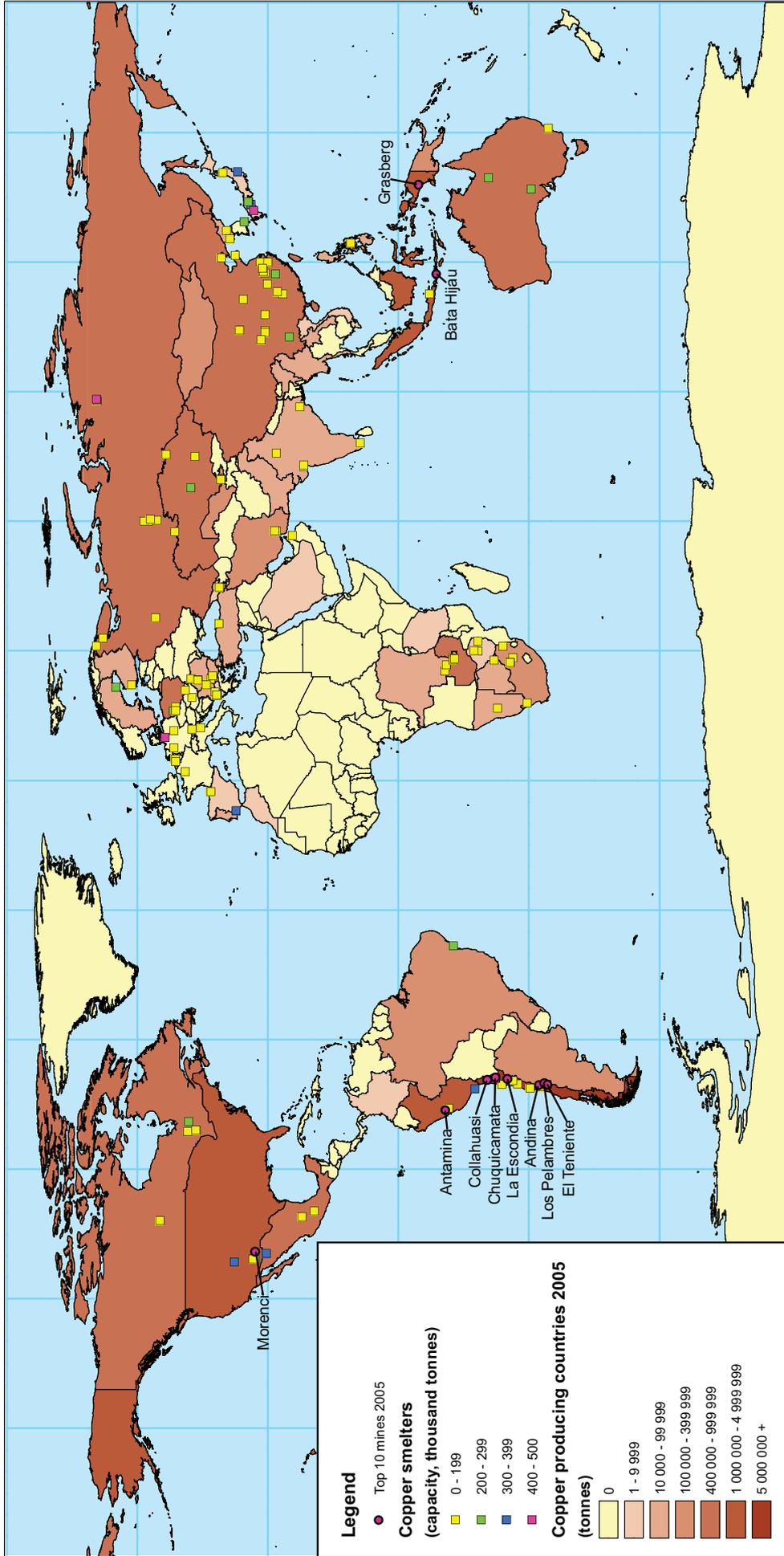


Figure 10 2005 copper producing countries, top 10 mines and 2002 copper smelters. Source: ESRI ArcWorld Supplement (countries 2005 map), USGS (smelter data 2002), British Geological Survey World Mineral Statistics (production data 2005), other data derived from company annual reports (top 10 mines 2005).

World trade

Most international copper trading takes place on three major metals exchanges:

- London Metal Exchange (LME) — copper is traded in dollars in 25 tonne lots;
- New York Commodities Exchange (COMEX) — trading is based on 25 000 pounds of copper quoted in dollar cents;
- Shanghai Futures Exchange (SHFE) — five tonne lots of copper are quoted in renminbi.

Stockpiles of the metals are held in exchange warehouses worldwide. The levels of the stockpile reflect the supply and demand characteristics of the physical market. Copper traders use copper futures and options to manage future price risk, and copper contracts may also be used as investment vehicles. The most important copper products in international trade in 2005 were refined copper (57%), concentrate (36%) and blister copper (7%). In addition to refined copper, trade in semi-fabricated products and copper alloys has grown rapidly in recent years.

During the last decade there has been a major relocation of global manufacturing capacity towards the emerging

economies of central Asia, in particular, China. The impact of these changes is obvious in the natural resources markets where direct copper usage is shifting from developed countries to newly industrialising nations. This has had a significant influence on copper trade flows worldwide.

Chinese imports of copper concentrates have increased rapidly since 2002, driven by extensive growth in smelting capacity. Japan and China are the two largest importers of copper concentrate worldwide (Figure 11). Chile accounted for 40% of copper concentrate supplied to China in 2005 and Chilean imports to China may increase further following the signing of a Free Trade Agreement. Peru is also a significant trade partner with China accounting for 16% of Chinese copper concentrate imports. Chile, which produces over a third of all copper globally, dominates the export market for both copper concentrate and refined copper (Figure 11 and 12). Chile has recently reviewed trade links with India through the signing of a Partial Access Agreement strengthening trade links with central Asia. In an attempt to improve security of supply and access to raw materials, China has sought partnerships with major copper-producing countries and companies.

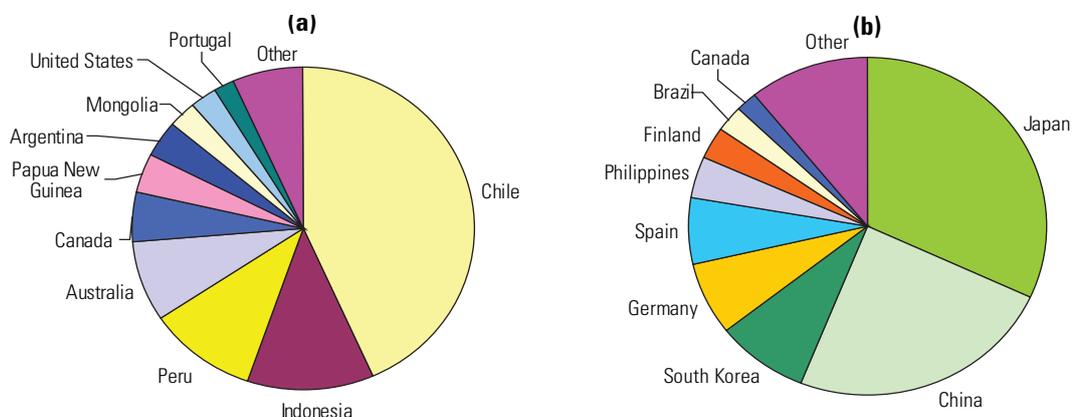


Figure 11 Trade in unrefined copper in 2005 (a) Exports (b) Imports. Source: World Metal Statistics.

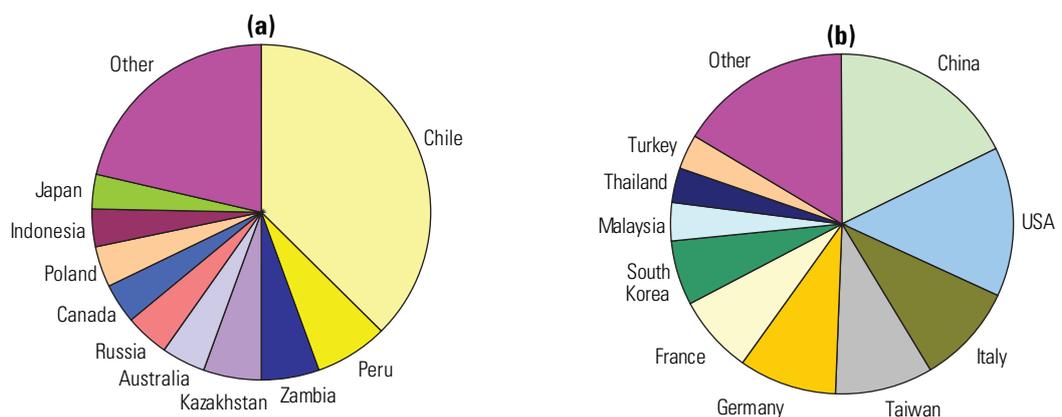


Figure 12 Trade in refined copper in 2005 (a) Exports (b) Imports. Source: World Metal Statistics.

An agreement between China's largest metals trading company, Minmetals, and the world's largest copper producer, Chile's Corporación Nacional del Cobre de Chile (Codelco), aims to ensure a long-term stable copper supply to China. The deal provides China with 55 000 tonnes of refined copper each year for over 15 years in exchange for help from China in developing projects in Chile. The European Union is heavily dependent on the refining and smelting of concentrates imported from countries such as Australia, Chile and Indonesia and recycling of production scrap or end-of-life products.

Prices

The price paid for copper on the metal exchanges primarily reflects global balances of copper supply and demand, but may be significantly affected by speculative activity, currency exchange rates and market news.

Copper demand and price typically reflect global economic cycles and, as a result, the copper price has historically experienced

major fluctuations (Figure 13). There were times in the 1990s when the copper price approached \$3000/tonne. However, for a five-year period up to the end of 2003 copper prices were relatively stable trading between \$1400 and \$2000/tonne. Towards the end of 2003 and early 2004 prices began to increase, reaching \$4500/tonne by the end of 2005. Many analysts at the time suggested this elevated copper price was not sustainable. However, the price continued to escalate in 2006. Although the price of copper currently appears very high in terms of US\$/tonne, in real⁴⁷ terms the current price is not quite as exceptional as it seems in nominal⁴⁸ terms. Real copper prices followed a general downward trend up to 2002 whilst the nominal price of copper has increased, with spectacular gains since 2003 (Figure 13).

The copper market was exceptionally strong during 2006 with copper prices averaging \$6700/tonne over the whole year, an 83% increase over 2005 (Figure 15). During the first five months of 2006, copper prices continued their upward trend and in May the LME spot price reached a record-high of \$8780/tonne, with an average price for the month of \$8044/tonne.

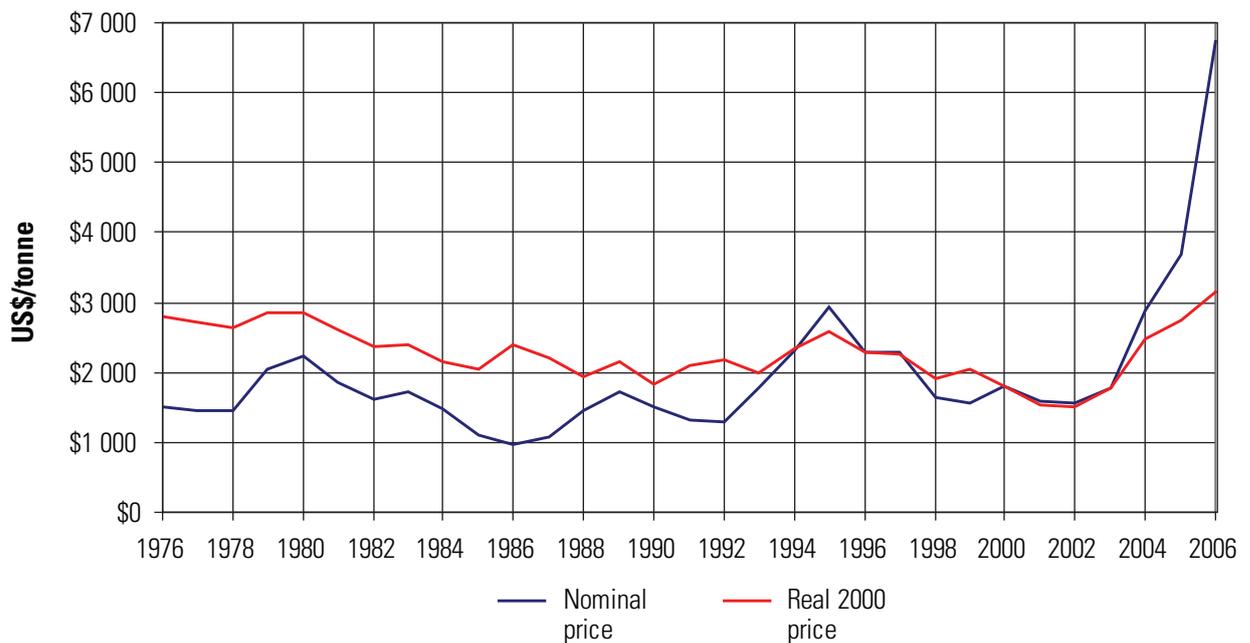


Figure 13 Historical spot price for copper 1976–2006. Derived from: *Metal Bulletin*. Real price adjusted for changes in the value of money compared to 2000.

⁴⁷Real price: is adjusted for changes in the value of money.

⁴⁸Nominal price: ignores changes in inflation and other factors.

Copper

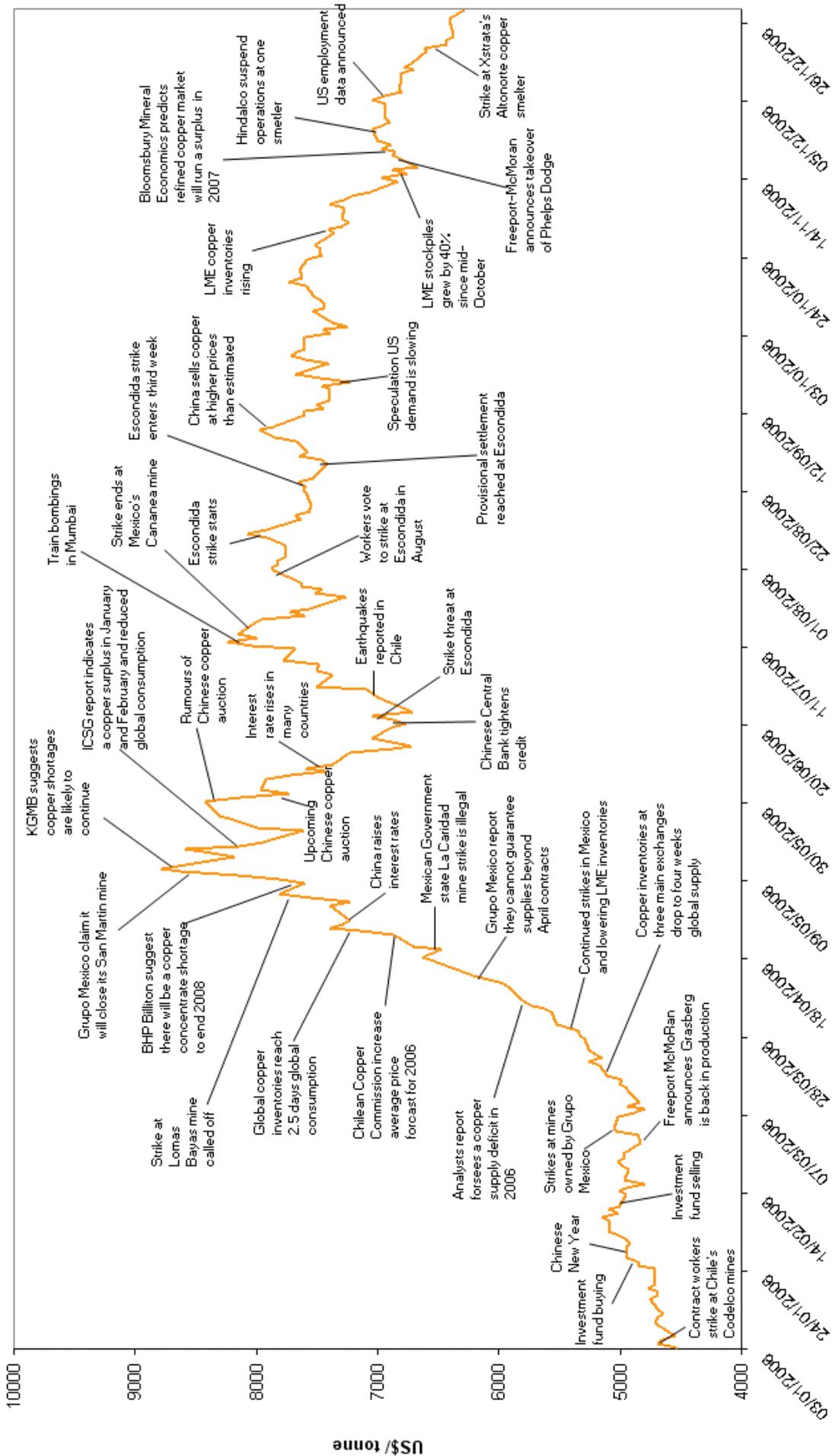


Figure 14 Key factors influencing copper prices in 2006. Derived from: Metal Bulletin, Copper Spot LME Daily Official. BGS © NERC.

The deficit in the availability of refined copper experienced during the previous three years persisted into 2006 resulting in tight supply and critically low exchange levels, amounting to less than three days global consumption at times. The supply-demand imbalance ensured prices reacted strongly to market developments resulting in considerable volatility and price spikes. Higher metal prices resulted in increased speculative demand for copper as an investment. Global mine production in 2006 was lower than expected as a result of production problems and labour disputes resulting in strikes in key copper-producing countries. Grupo Mexico experienced considerable losses as a result of strikes at a number of its operations. Production at Chile's Escondida mine was interrupted for most of July by labour disputes causing loss of an estimated 45 000 tonnes of contained copper. At total of around 500 000 tonnes of production, or three percent of global production, is estimated to have been lost as a result of disruptions associated with labour disputes and other operational problems during 2006.

By the end of 2006, copper prices had fallen considerably from the record highs in May of that year. This reflected moderation in demand, recovery of global mine output from disruptions earlier in the year and growing exchange inventories. In addition, escalating oil prices and an abrupt decrease in United States house building signalled possible global economic slowdown resulting in decreased demand for industrial materials. Exchange inventories reached a low of 153 000 tonnes in July 2006 but had risen to over 210 000 tonnes in November. At the end of 2006, however, prices remained 45% higher than at the end of the previous year.

The underlying reason for rising metal prices during the last three years has been growing demand from emerging economies, primarily China. Copper consumption has been driven by rapid expansion of the Chinese electronics and construction sectors both of which are heavily dependent on copper. China accounts for around 25% of world copper consumption. India has also shown strong signs of

growth and its automotive and construction sectors are rapidly developing. The copper consumption picture during 2006 was complex, with conflicting reports regarding Chinese consumption. In 2006, world copper consumption increased by only four percent over 2005 to 17.4 million tonnes, a much smaller increase than in previous years. Estimates suggest Chinese copper consumption declined by around one percent despite continued strong economic growth, although unreported State Reserve Bureau copper sales cloud China's true consumption figures.

Chinese copper imports decreased in 2006 in response to higher prices and increased domestic availability from domestic cathode production, state reserves and greater scrap recycling. According to reports by the International Copper Study Group (ICSG), during the first 9 months of 2006 there was a global copper surplus of more than 80 000 tonnes compared with a production deficit of more than 300 000 tonnes during the same period in 2005.

Developments in China and the USA, the world's largest copper consumers, are likely to have the greatest impact on future global copper consumption. Copper demand in China is predicted to continue growing, driven by further growth in the construction sector as well a requirement to replenish Chinese inventories which were depleted during 2006.

Rising copper prices in recent years have led to investment in new production capacity, expansions at key operations and previously uneconomic projects becoming viable. However, the large projects in particular have considerable lag times and some have encountered problems. Global copper mine production is forecast to grow by six percent in 2007. Phelps Dodge commissioned their Cerro Verde expansion in Peru in early 2007, adding around 145 000 tonnes a year to production and a number of smaller operations are also due to come online. Record copper prices have also spurred consolidation within the sector. Notable is Freeport-McMoRan Copper & Gold Inc's takeover of Phelps Dodge to create the world's largest publicly traded copper producer.

Alternative technology

Secondary production: recycling

Secondary production, derived from the recycling of copper scrap, accounts for around two thirds of total copper production (Figure 15). Copper and its alloys can be continuously recycled without diminishing their useful properties. Producing copper from recycling takes approximately one sixth of the energy required to produce copper from ore (because the oxidation and reducing stages are not necessary). As a result, a large proportion (~80%) of all the copper that has ever been mined is still in use today.

The way in which copper scrap is recycled depends on its purity. High purity copper or specific alloy mixes are collected and segregated and can simply be re-melted in a smelter and recast for use in subsequent fabrication. With alloys, minor adjustments can be made to the composition while it is molten, in order to bring the resulting mixture up to specification. Less pure or mixed scrap can be smelted and directly recast for use in non-electrical applications where purity is not so critical, such as plumbing and roofing. Alternatively, scrap can be mixed with pure copper to 'dilute' the impurities, or, if necessary, cast into anodes and electrolytically refined, as in the final stages of primary copper processing. If the scrap includes certain specific materials, for example tinned or lead-soldered copper, it may be more economic to take advantage of these contaminants, rather than trying to remove them. Certain alloys which contain those metals, such as gunmetal and bronze, can use this scrap as smelter feedstock.

It is important that the waste streams of copper scrap for recycling are segregated to avoid unnecessary contamination of the copper with impurities which will involve extra processing to remove. Scrap can be classified in several ways, but it can broadly be sub-divided into two categories, new scrap and old scrap.

New Scrap

This includes all scrap from processing to manufacturing, before it enters the consumer market. New scrap comprises:

- process scrap — includes processing residues, slag, fines and drosses⁴⁹. It is usually 100% reused immediately within the plant.

- home scrap or run-around scrap - is the punching, borings, turnings and cuttings generated in foundries and mills which are taken back to the casting shop, where it is re-melted and cast into cakes.
- prompt scrap, industrial and return scrap — are the stampings, cuttings and turnings produced when the semi-fabricated products are converted into parts in metal workings shops. It is usually returned to the mill that supplied it.

Old Scrap

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

- end-of-life vehicles (ELV) — the copper is recovered and recycled from radiators, engine parts and electronic components.
- construction & demolition (C&D) — includes wiring, roofing and plumbing materials.
- which can be difficult and expensive to separate as they may contain hazardous materials, such as mercury or batteries.

Substitutes

Copper in electrical applications

Silver is the best electrical conductor known to man and copper is the second, but silver is too expensive to be economically used in electrical wires. Other cheaper alternatives include aluminium. However, non-copper wires can 'creep' causing connections to loosen and therefore require checking periodically. Also anti-oxide paste must be applied where the wires are joined and connected, as anodic corrosion can cause the aluminium to disintegrate. Aluminium oxide does not conduct, although copper oxide does. A combination of the two metals has been used in bimetallic copper-clad aluminium (CCA) wire, which is an aluminium core covered with copper cladding. It costs and weighs less, and handles and installs more easily than solid copper wire. In certain telecommunications applications optical fibre can replace copper wire.

⁴⁹Drosses: solid metal processing waste.

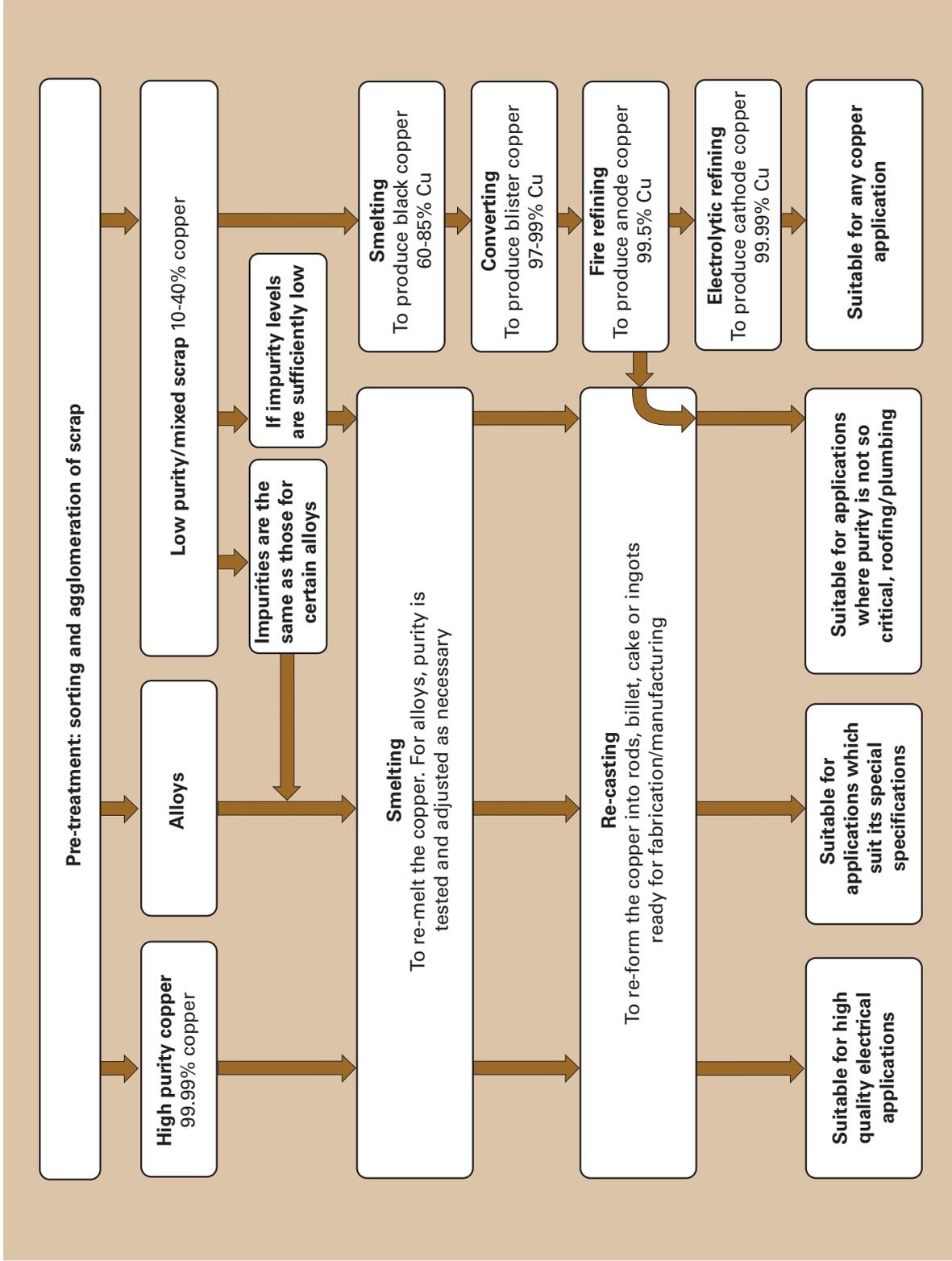


Figure 15 The copper recycling process.

Water pipe and plumbing fixtures

Aluminium and plastics are the two most common substitutes for copper for this application. There is an aluminium plastic composite water piping system, which is made of aluminium tube, laminated inside and out with plastic, to create piping that is lightweight, flexible, strong, corrosion-resistant and that can be easily bent or formed by hand. Plastics include CPVC, PVC and PEX which are cheaper, have reduced noise, are more energy efficient, have less condensation than copper, no corrosion or scale build up, no pin hole leaks and are chlorine resistant. They are also easier to install and modify at a later stage.

Heat exchangers

Copper is commonly used for heat exchangers filled with water or ethylene glycol with water. Alternative materials include steel, titanium, aluminium and plastic, each of which lend themselves to particular applications:

- Stainless steel heat exchangers can operate at higher temperatures and are more rugged than copper ones. They are ideal for heating or cooling corrosive fluids in chemical, pharmaceutical, and refining processes.
- Titanium units can also tolerate high temperatures and high pressures, with superior corrosion resistance. They are also 5–10 times lighter than their steel counterparts, although they are much more expensive. They are often used in marine applications.
- Aluminium is mainly used in cold temperature applications (to -270°C). It has good heat transfer performance, relatively high pressure ratings and is lighter than other metals.
- Plastic — polyvinylidene fluoride, polypropylene, and polyethylene construction is specifically useful for highly corrosive gases, for example in the condensation recovery of acidic components from biological waste incineration.

Automotive Radiators

In the past automobile radiators were largely made of brass, because of its machinability, and thermal conductivity properties. A common substitution is now aluminium. This is because aluminium is lighter and less affected by corrosion from the coolant. In addition there were environmental concerns

about the lead (brass is a copper-lead alloy) in manufacturing and repair shops. The lead-tin solder used in brass radiators can also 'creep' and cause leaks.

Miscellaneous

Steel now substitutes for copper used for artillery shell casings because it is cheaper. Aluminium is often used in cooling fins and refrigerator tubing.

Research and Development

Research into improving the efficiency and cost effectiveness of extracting and processing copper is ongoing.

A variety of chemical and biological techniques to leach copper, particularly from sulphide ores, is being developed, with many pilot plants in operation around the world. Some of these processes have already entered commercial use, such as the BIOCOP™ process used by BHP Billiton in Chile, Hydrocopper[®] developed by Outokumpu and commissioned in Erdenet, Mongolia.

These techniques include leaching under elevated pressure and/or under raised or controlled temperatures. Others involve addition of catalysts (such as silver ions), chemicals (such as chlorides), or bacteria cultivated under particular conditions (called biohydrometallurgy or bio-leaching). Bacteria can be used to speed up and optimise copper yields under certain conditions. The effectiveness of the process depends on the ore mineralogy and how easily the optimum conditions can be maintained.

As hydrometallurgical technology is refined it will enable lower grade ores which had previously been considered waste, to potentially yield copper in a cheaper, more efficient and environmentally friendly way than the traditional pyrometallurgical processing route.

Copper's versatility ensures that new uses continue to be explored. Expanding markets are in the construction, electrical and marine transport industries. Health and medical applications are beginning to take advantage of the natural antibacterial properties of copper metal. These include applications such as lining water containers in countries where access to clean water is limited and use in hospitals and food preparation areas.

Focus on Britain

Known occurrences

Copper mineralisation occurs in many areas of Britain and although there is currently no copper production, Britain has an important history of copper mining. There is evidence of Bronze Age copper mining in south-west England and in North Wales. In Cornwall, copper and tin were traded with the Phoenicians as early as 1500 BC. The Parys Mountain Mine in Anglesey, North Wales, which may have been mined during Roman times, was the world's largest copper producer for a period in the eighteenth century (Figure 16). Returns for the whole of the nineteenth century show Britain to be the world's fourth largest copper producer, accounting for nearly ten percent of total production. Extraction fell rapidly towards the end of the century and the last UK copper mine, the Wheal Jane Mine in Cornwall, closed in 1991.

The decline of British copper mining was mainly the result of falling metal prices and competition from overseas (Chile, Australia and USA). Deposits were not of sufficiently high grade or abundance to remain economic. After a long period of relatively low priced copper, the recent upturn has resulted in some of the old mines and

newer discoveries being re-evaluated such as Anglesey Mining's Parys Mountain project in North Wales.

The following types of copper mineralisation have been identified in the UK (Figure 17). A more detailed description of localities and specific deposit types of copper mineralisation found in the UK is covered by the report 'Exploration for metalliferous and related minerals in Britain: a guide'.

Porphyry deposits

Disseminated copper mineralisation, locally with gold enrichment, occurs at several localities associated with Caledonian⁵⁰ intrusive rocks. The best known deposit is Coed y Brenin, near Dolgellau in North Wales. This deposit contains 200 million tonnes grading 0.3% Cu, with trace gold. Coed y Brenin lies within the Snowdonia National Park and proposals to mine it in the 1970s met considerable opposition. Up until 1914 a breccia pipe containing copper-gold mineralisation was worked at the Glasdir mine close to Coed y Brenin, with total production of about 75 000 tonnes at 1.5% Cu. In the south-west Highlands of Scotland, disseminated polymetallic mineralisation of epithermal-porphyry style is found at Lagalochan.



BGS © NERC

Figure 16 Parys Mountain mine in North Wales.

⁵⁰Caledonian: a period of mountain building from middle Ordovician to mid-Devonian times, resulting in deformed rock and granitic intrusions over much of Scotland.

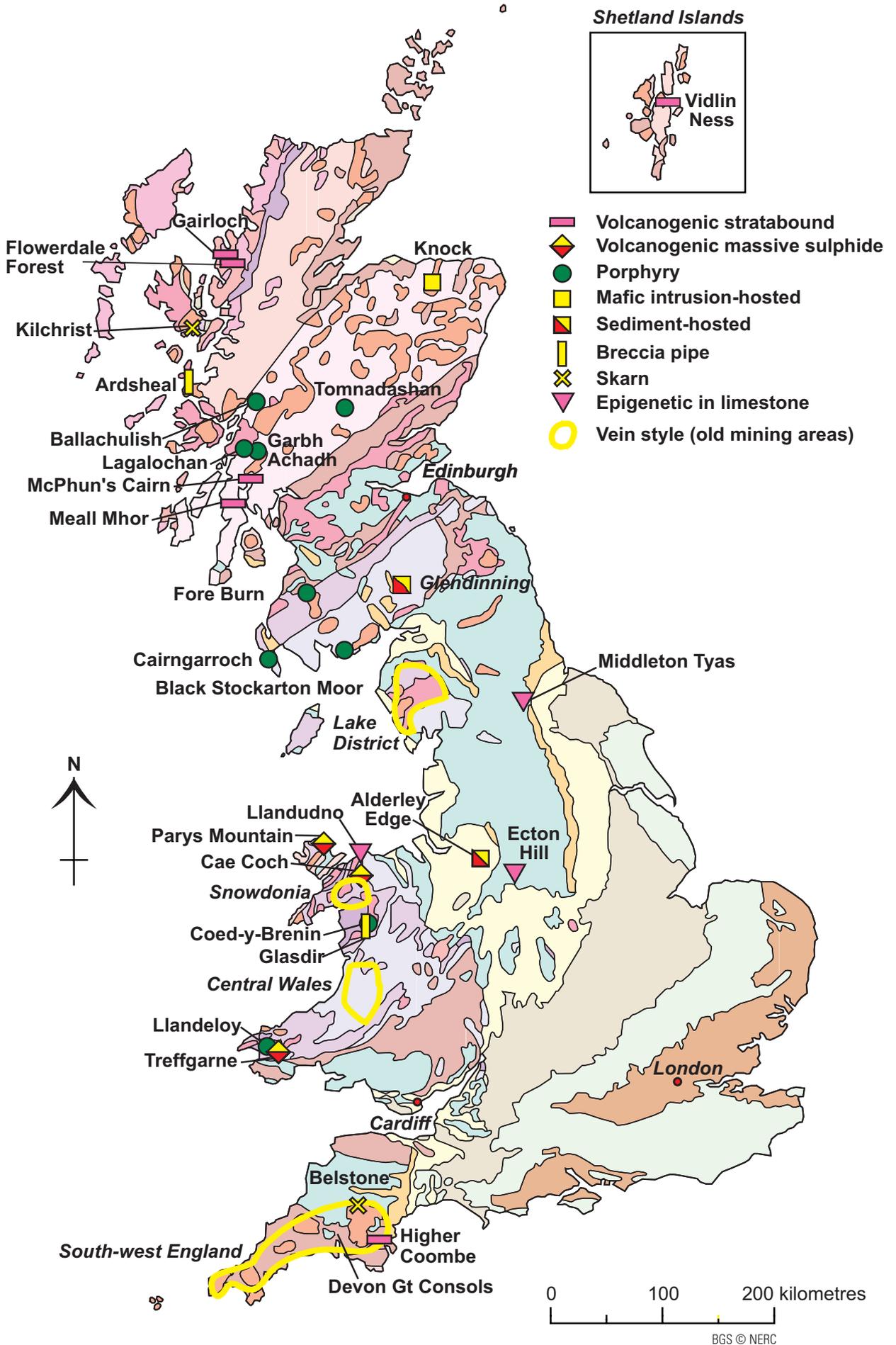
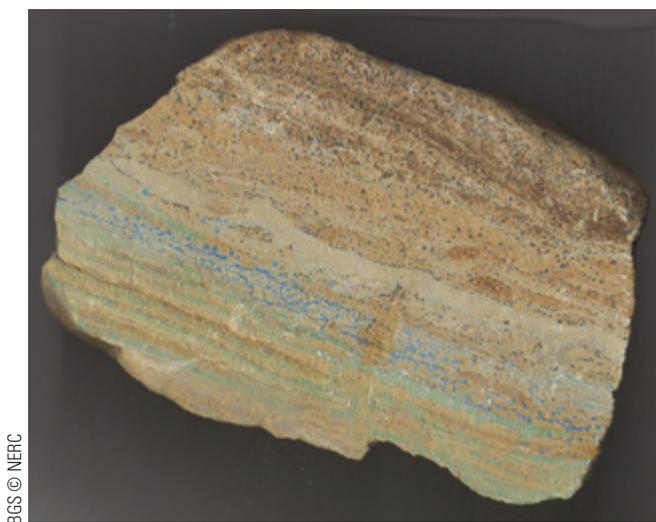


Figure 17 Distribution of major copper occurrences in Britain.

Red-bed deposits

Triassic (250 to 210 million years) red-beds in the English Midlands are locally enriched in copper. The sandstones⁵¹ and conglomerates⁵² of the Sherwood Sandstone Group in the Alderley Edge area of the Cheshire Basin are historically most productive. The ore is dominated by copper carbonates with small amounts of lead, cobalt, zinc and traces of gold (Figure 18). Barytes is commonly associated with the ore minerals. The mineralisation preferentially develops in traps created by faulting⁵³ and the overlying rocks. The deposits, which were worked from the late 1600s to the 1920s, had an estimated grade of 2.1% Cu and produced around 3200 tonnes of recovered metal.



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Figure 18 Mineralised sandstone from Alderley Edge.

Volcanic massive sulphide (VMS) and SEDEX deposits

Parys Mountain on Anglesey in North Wales is the most significant VMS deposit known in Britain and a historically important copper producer. The deposit was extensively mined by open pit and underground methods, producing around 300 000 tonnes of copper in the late 1700s.

Mineralisation at Parys Mountain is associated with highly altered volcanic rocks and mudstones⁵⁴. In 1992, Anglesey Mining determined a geological resource⁵⁵ of

6.5 million tonnes with an average grade of over 10% combined Zn, Cu and Pb, with Au and Ag. Over the last 10 years extensive geological studies and drilling have been conducted at the site. According to recent reports, Anglesey Mining are planning to develop the project, focusing on the near-surface part of the deposit which has an estimated copper resource of 2.15 million tonnes at 0.36% Cu. The only other deposit of this type known in Wales is the Cae Coch massive pyrite deposit of Ordovician (505 to 440 million years) age in Snowdonia.

Besshi-type⁵⁶ copper-zinc-gold mineralisation is found in basic Lewisian⁵⁷ rocks near Gairloch in north-west Scotland. Two laterally extensive sulphide horizons were located, one of which can be traced for over 6 km and consists mainly of iron sulphides. The other, with a length of at least 1 km, comprises a 4 m thick quartz-carbonate schist⁵⁸ with pyrite, pyrrhotite, chalcopyrite and gold. The deposit was extensively drilled in the late 1970s. Reported grades were about 1% Cu, 0.5% Zn and 1 g/t Au which were not economic at that time. Stratabound sulphides enriched in Pb-Zn-Ba and locally copper are widespread in the Dalradian⁵⁹ rocks of Scotland. The richest deposit is at Vidlin Ness in the Shetland Islands where drilling revealed stratabound sulphides reaching 10 m thick and grading up to 1.19% Cu and 1.27% Zn. In south-west England stratabound base-metal mineralisation occurs locally in Devonian (410 to 360 million years) and Carboniferous (360 to 290 million years) sedimentary and volcanic rocks. Drilling intersected low-grade disseminated and veinlet copper mineralisation near Higher Coombe in Devon.

Magmatic sulphide deposits

Layered mafic-ultramafic intrusions of late Caledonian age underlie large areas in north-east Scotland and have been the subject of exploration for nickel-copper and PGE mineralisation. Exploration of the Aberdeenshire mafic-ultramafic intrusives in the 1960s and 1970s led to the drilling of the Knock intrusion and identified a geological reserve of 3 million tonnes grading 0.52% Ni and 0.27% Cu. Work at Arthrath, near Aberdeen, intersected weakly mineralised intervals of nickel-copper sulphides over an extensive area. Alba Minerals is currently prospecting the area and have drilled new holes to verify historical data.

⁵¹Sandstone: a sedimentary rock composed of sand-size mineral or rock grains.

⁵²Conglomerate: a coarse-grained sedimentary rock typically containing rounded particles.

⁵³Fault: a fracture in the Earth's surface along which the opposite sides have moved.

⁵⁴Mudstone: a fine-grained sedimentary rock composed mainly of silt-clay sized particles.

⁵⁵Resource: a concentration of material in the Earth's crust of economic interest.

⁵⁶Besshi-type: a sub-division of VMS deposits based on metal content (Section 1.3.1).

⁵⁷Lewisian: highly deformed rocks in north-west Scotland.

⁵⁸Schist: a medium-grade metamorphic rock containing platy and elongated minerals.

⁵⁹Dalradian: a succession of Late Precambrian (4000 to 590 million years) and Cambrian (590 to 505 million years), mainly sedimentary rocks found in Scotland and Ireland.

Vein-style deposits

These are associated with either granitic intrusions (south-west England), volcanic rocks (North Wales and Lake District) or sedimentary basins (Central Wales). Historically vein deposits have been important sources of copper in Britain, particularly those in south-west England, which was the world's main source of copper in the first half of the nineteenth century. The mineralisation in this region occurs in association with Hercynian⁶⁰ granites. The main copper mineralisation generally occurred above the tin-bearing parts of the system.

Epigenetic deposits in limestones

At Ecton Hill in the Southern Pennine Orefield about 100 000 tonnes of ore containing 15% Cu were extracted in the 1800s from two pipe-like vertical orebodies and associated veins hosted by limestone. Small but very high-grade copper deposits have also been mined in cavernous Carboniferous limestones near Llandudno in North Wales, at Llanymynech in the Welsh Borders and near Middleton Tyas in Yorkshire.

Consumption

Britain is a major consumer of copper and copper-containing products. The metal is used principally in manufacturing (electronics, cars, white goods), building (electrical systems), chemicals (dyes, explosives, preservatives) and agriculture.

In 2005 the United Kingdom consumed 165 400 tonnes of refined copper, which equates to one percent of total world consumption (Figure 19). Within Europe, Britain is the eighth largest consumer of copper goods, after Poland, Spain, Belgium, France, Italy, Russia and Germany (Germany has the largest consumption in Europe).

British consumption rose through the 1990s to a peak of 408 500 tonnes in 1997 and has since declined by nearly 40%.

The European average consumption per capita is 6.4 kg copper, whereas the British figure is less than half of that, at 2.8 kg per capita (World Bureau of Metal Statistics and United Nations Department of Economic and Social Affairs).

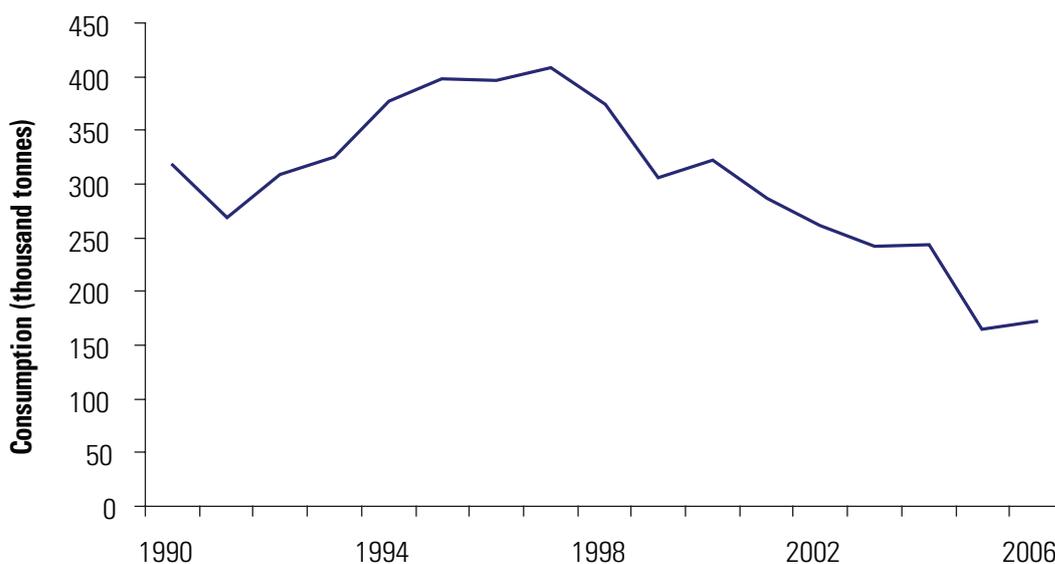


Figure 19 Consumption of refined copper in the UK from 1989 to 2006. Source: World Bureau of Metal Statistics.

⁶⁰Hercynian (Variscan): a period of mountain building during the Carboniferous which resulted in deformed rock and granitic intrusions over much of south-west England and western Europe.

Further reading and selected references

Useful contacts for further information

London Metal Exchange	www.lme.co.uk
New York Metals Exchange	www.nymex.com
Copper Development Association	www.copper.org
International Wrought Copper Council	www.coppercouncil.org
European Copper Institute	www.eurocopper.org
International Copper Association	www.copperinfo.com
International Copper Study Group	www.icsg.org
Specific mining project information	www.mining-technology.com
British Columbia Mineral Deposit Profiles	www.em.gov.bc.ca
Natural Resources Canada	www.nrcan-rncan.gc.ca/com
United States Geological Survey	www.minerals.usgs.gov
World Bureau of Metal Statistics	www.world-bureau.com

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