

Definition, mineralogy and deposits

Definition and characteristics

Nickel is a lustrous, silvery-white metal which is hard, ductile, malleable, and can take a high polish. It has fairly low thermal and electrical conductivities and can be magnetised. Properties that are important in industrial applications include resistance to oxidation and to corrosion by alkalis, strength at high temperatures, and the ability to form alloys with many other metals. Key physical properties and other features are summarised in Table 1.

In the Earth's crust nickel abundance averages 80 parts per million (ppm), but, as it is greatly concentrated in the core, it is actually the fifth most common element on the planet. Nickel occurs with iron in meteorites, and in small quantities in plants, animals and seawater.

Nickel is a transition group metal with 14 known isotopes, five of which are stable. It has the same oxidation state (+2) as, and a similar ionic size to, iron and other similar transition group metals, so it can substitute for iron in many minerals.

Mineralogy

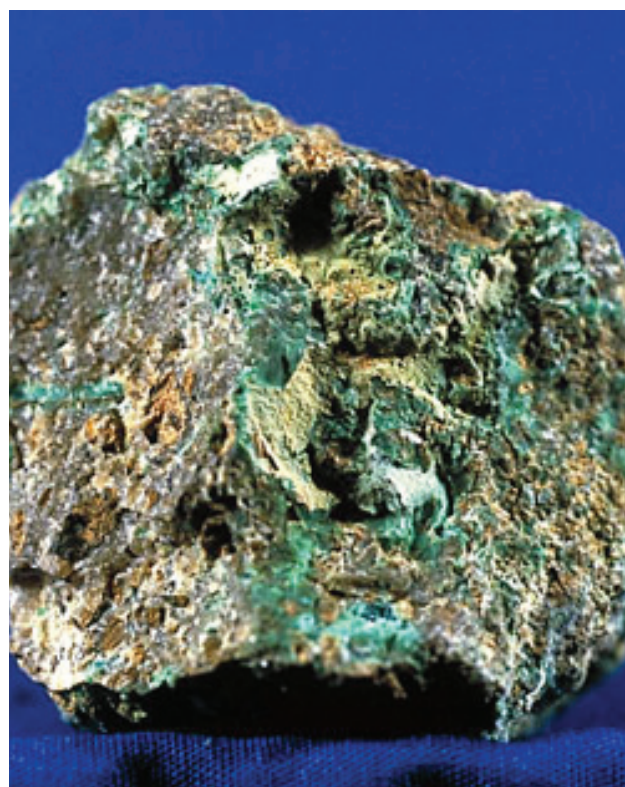
There are numerous nickel-bearing minerals, although some of these are very rare and a few occur only in meteorites. Nickel may substitute for other elements, especially iron and cobalt, in many minerals.

Economic concentrations of nickel-bearing minerals occur as sulphides and in laterites. Pentlandite (see Table 2) is the most important nickel sulphide mineral in economic deposits where it occurs with pyrrhotite, chalcopyrite and pyrite in mafic and ultramafic (iron- and magnesium-rich) igneous rocks. The main nickel-bearing minerals in laterites are garnierite and nickeliferous limonite.

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Symbol	Ni	
Atomic number	29	
Atomic weight	58.6934	
Density at 293 K	8902	kg/m ³
Melting point	1453	°C
Boiling point	2732	°C
Crystal structure	face centred cubic	
Hardness	3.8	Moh
Electrical conductivity	22	% (International Annealed Copper Standard)

Table 1 Selected properties of nickel.



Garnierite (green), hydrous nickel silicate, in laterite.

Name	Group	Formula	Most common mode of occurrence	Example deposits
Pentlandite	Sulphide	$(\text{Fe,Ni})_9\text{S}_8$	In mafic intrusions or remobilised phase after metamorphism.	Noril'sk, Russia. Bushveld, South Africa. Voisey's Bay, Canada. Kambalda, Western Australia.
Ni replacement in pyrrhotite	Sulphide	$\text{Fe}_{1-x}\text{S}_x$	In mafic intrusions.	Noril'sk, Russia. Bushveld, South Africa. Voisey's Bay, Canada. Kambalda, Western Australia.
Garnierite	Hydrous nickel silicate (serpentine)	$(\text{NiMg})_3\text{Si}_2\text{O}_5(\text{OH})_4$	In laterites related to ultramafic rocks.	New Caledonia. Sulawesi, Indonesia. Cerro Matoso, Columbia.
Nickeliferous limonite	Hydroxide	$(\text{Fe,Ni})\text{O}(\text{OH})$	In laterites related to ultramafic rocks.	New Caledonia. Sulawesi, Indonesia. Euboea, Greece.
Millerite	Sulphide	NiS	Mafic intrusions where metasomatism has remobilised Ni and S from pentlandite; also from metamorphism of olivine.	Silver Swan, Western Australia. Sudbury, Canada.
Niccolite	Nickel arsenide	NiAs	Hydrothermal replacement of pentlandite in mafic intrusions or metasomatism of low-sulphur mafic rocks. Seafloor manganese nodules.	Cobalt, Ontario. Widgiemooltha Dome and Kambalda, Western Australia.
Nickeliferous goethite	Hydrated oxide	$(\text{Fe,Ni})\text{O}(\text{OH})$	In laterites related to ultramafic rocks.	Koniambo Massif, New Caledonia.
Siegenite	Sulphide	$(\text{Ni,Co})_3\text{S}_4$	Hydrothermal veins.	Siegen, Germany. Jachymov, Czech Republic.

Table 2 The most common nickel-bearing minerals found in economic deposits.

Deposits

The majority of economic nickel deposits occur in two geological environments: in magmatic sulphides and in laterites. Sulphide deposits, which are the primary source of mined nickel at present, may be formed by fractional crystallisation¹ within magma chambers or in ancient lava flows. Sulphide ore grades range from 0.15% to around 8% Ni, but 93 per cent of known deposits are in the range 0.2–2% Ni (Hoatson, 2006). Nickel-bearing lateritic ores, with average nickel content of 1–1.6%, are formed by tropical and sub-tropical surface weathering. Table 3 summarises these and other types of nickel deposit.

Laterites currently account for around 70 per cent of nickel contained in land-based deposits but contribute only 40 per cent of world production. It is anticipated that increasing demand for nickel will be met largely by supply from lateritic deposits as processing techniques improve.

Major deposit classes

Stratabound deposits

Slow cooling in large mafic and ultramafic intrusions causes different minerals to crystallise and settle out of the magma in discrete layers. When the magma becomes saturated with sulphur an immiscible sulphide liquid forms into which nickel partitions preferentially. On account of its density, this liquid settles out to form discrete sulphide-rich layers which may display sedimentological features such as grading and troughs. Repetitive layering of sulphides can form due to flow dynamics and recharging in large magma chambers. The main sulphide minerals are pentlandite and pyrrhotite which often occur between and within olivine-rich layers. Platinum-group metals (PGM) may also be enriched in these deposits.

Sulphide immiscibility may result from various processes including crustal contamination and magma mixing. Ore grades vary a great deal depending on the individual characteristics of the intrusion but typical economic grades range from 0.2–3% Ni.

Deposit type	Brief description	Typical economic grades	Major examples
Stratabound	Fractional crystallisation and other processes in large magma chambers cause deposition of discrete nickel and copper sulphide phases and platinum-group minerals.	0.2–3%	Bushveld Igneous Complex, South Africa. Great Dyke, Zimbabwe.
Basal	Sulphur saturation of mafic magma causes dense nickel sulphides to be concentrated in basal sections.	0.6–2%	Noril'sk, Russia. Voisey's Bay, Canada. Jinchuan, China.
Impact melt	Unique class of deposits derived from melt produced by extra-terrestrial meteorite impact.	1.2% average	Sudbury, Ontario, Canada.
Deposits in extrusive ultramafic rocks	Ultramafic komatiite flows become sulphur saturated by host rock assimilation and differentiation. Dense nickel sulphides and platinum-group minerals are deposited in depressions in footwall rocks.	1.5–8%	Kambalda, Australia. Mount Keith, Australia. Thompson Belt, Canada.
Laterite deposits	Tropical weathering of nickel silicates and sulphides in ultramafic bodies causes nickel to become enriched in residual weathered rocks (regolith).	0.9–3%	Koniambo Massif, New Caledonia. Cerro Matoso, Colombia. Murrin Murrin, Australia.
Hydrothermal remobilised deposits	Crystallisation from fluids sourced in ultramafic intrusions depositing nickel minerals in cavities such as cracks, fissures, pore spaces or stockworks.	0.4–1.2%	Avebury, Tasmania.
Manganese nodules	Ferromanganese oxide concretions on the sea floor enriched in nickel by extraction from seawater and pore fluids from muds.	0.5–1.3%	None.

Table 3 Major nickel deposit types classified by geological setting and morphology of the ore.

¹ Fractional crystallisation is the precipitation and segregation of minerals from magma. The residual magma and minerals subsequently crystallising progressively change chemical composition.

One of the best known examples of this type of deposit is the Merensky Reef, which is found in the Bushveld Complex in South Africa, where nickel is extracted as a by-product of platinum-group metals. Here, very slow cooling in a major magma chamber has caused the settling-out of many discrete mineral phases to form extensive layers.

Basal deposits

If a mafic-ultramafic melt becomes saturated in sulphur, an immiscible sulphide phase will form which strips nickel from the residual magma. This relatively dense phase may be concentrated on footwall contacts and in basal sections of the igneous body as well as in feeder conduits. Mineralisation occurs as nickel, cobalt and copper sulphides, possibly with associated platinum-group minerals. The grade of these deposits varies greatly, depending on the individual ore-forming mechanism, but is generally in the range 0.6–2% Ni.

Basal deposits exhibit a wide range of morphologies and ages. Many occur within Archaean greenstone belts (a linear volcanic and sedimentary belt 10–15 km thick older than 2500 Ma) where high heat flow led to the formation of a high proportion of mantle-derived ultramafic rocks. Due to the great age of these rocks the ores may be altered, mainly by metasomatism², remobilising nickel and sulphur from pentlandite and pyrrhotite and recrystallisation of olivine. This

can cause the nickel minerals to be concentrated as massive ore in the country rock. This style of mineralisation occurs in the Agnew Mine, Western Australia.

The largest nickel reserves are found in deposits of this type in the Noril'sk district of Russia. In this area the deposits are associated with the Permo-Triassic Siberian flood basalt suite and are hosted by coeval, elongate, thin mafic sills that intrude Devonian and Carboniferous continental sedimentary rocks including evaporites and coal. The genesis of these deposits is believed to be due to the focused ascent along regional structures of deep-sourced metal-bearing magmas. Interaction of these magmas with sulphur-bearing sedimentary rocks such as evaporites led to the separation of an immiscible sulphide liquid. Fe-Ni-Cu sulphide minerals were deposited from this liquid at certain favourable sites. Continued passage of fresh magma along the same conduit, feeding the overlying volcanic pile, led to the production of large, high grade Ni-Cu-PGE deposits.

Another major world-class nickel deposit of this type is Voisey's Bay, Labrador, Canada. Mineralisation in this deposit occurred through magma fractionation and crustal contamination by graphitic gneisses³ causing sulphur saturation and immiscibility. The sulphide phase was then



Construction of the new Nickel Rim South project in Sudbury, Canada. Courtesy of Xstrata Plc.

² During metasomatism rock interacts with aqueous fluids and chemical components may be introduced. The rock remains in a solid state.

³ Gneiss is a banded metamorphic rock, with composition similar to granite. Banding results from segregation of the various minerals present, typically into dark- and light-coloured layers. Individual mineral grains, often flattened parallel to banding, are large enough to be seen with the naked eye.

swept up by successive pulses of new magma into feeder conduits and into the overlying magma chamber. Voisey's Bay is similar to the Noril'sk deposit as fresh magma was depleted in nickel and platinum group elements by circulation with the sulphide phase. The immiscible sulphide phase was finally deposited when the turbulent high-energy magma flow passed through constrictions in the feeder system and into the upper magma chamber. Broadly similar enrichment and deposition mechanisms are believed to occur in other world-class deposits such as Jinchuan, China.

Impact-related deposits

The Sudbury Igneous Complex (SIC) in Ontario, Canada, has the second largest reserves of nickel in the world. The SIC is unique as it was formed by a large extraterrestrial impact. This caused intense magmatism by both melting on impact and subsequent unloading of the underlying mantle as the thickness of the crust was locally reduced by 50 per cent. This formed a large ultramafic magma chamber with high levels of crustal contamination. Assimilation of this silica-rich material caused a lowering of the solubility of sulphur in the melt and consequent sulphide mineral precipitation. Nickel-copper deposits, in some cases enriched in platinum-group elements (PGE), are found chiefly on the margins of the SIC but also extend locally into the footwall rocks as dyke-like offsets.

Deposits in extrusive ultramafic rocks

In this environment nickel is deposited from an immiscible sulphide liquid in rapidly crystallising ultramafic extrusive rocks. Sulphur saturation can occur as a result of cooling deep-sourced melts enriched in mantle-derived sulphides or by the assimilation of sulphide-rich sedimentary host rocks (such as evaporites or pyrite-rich shales). Due to the high density of the sulphide phase, deposits are typically located at the base of flows and can often be found in topographic lows in footwall rocks. Thermal erosion can also cause the sulphides to penetrate into the footwall. Above the basal contact there may be zones of both massive and disseminated sulphide minerals. Primary ores may show sedimentary-like structures indicating that flow dynamics of the lava and palaeotopography were important ore controls.

The most important deposits of this type occur in komatiites, high-temperature magnesium-rich ultramafic rocks aged 3800 – 2500 Ma from the Archaean Eon. These rocks are normally found with pillow basalts and metasedimentary rocks. Above massive basal and footwall

ores a zone of acicular (needle-like) olivine crystals may occur with massive sulphide ore trapped in between. Komatiites are generally metamorphosed leading to remobilisation of primary nickel ore. Mineralisation occurs as pentlandite, Ni-replacement pyrrhotite and occasionally millerite. The best known deposits of this type are found in the Kambalda Dome, Western Australia. The average grade for extrusive ultramafic deposits is about 3.3% Ni, although in other deposits elsewhere in the Yilgarn Craton grades can be as high as 7.7% Ni.

Laterite deposits

In subtropical and tropical climates intense weathering of ultramafic rocks may lead to nickel enrichment. Nickel dispersed in silicates and sulphides within the host rock is remobilised and deposited as hydroxides, limonite and goethite, in weathered layers near the surface and as silicates (garnierite) at deeper levels. Serpentine-rich zones in saprolite (a fine-grained clay produced by weathering of bedrock) at the base of laterites may restrict the circulation of groundwater and thus the amount of Ni enrichment. This also interferes with beneficiation due to individual grains needing to be crushed to liberate ore from gangue intergrowths. There is a wide range of economic grades in laterite deposits, from 0.4–1.2% Ni, generally lower than in those of magmatic origin.

Topography plays an important role in the formation of laterite deposits, even more so than the concentration of nickel in the source rocks. The most extensive deposits are found on gently dipping slopes where groundwaters freely circulate and weathering is promoted. 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 peridotites⁴ and ideal weathering conditions; here nickel can be enriched up to 30 times its original concentration in the bedrock source.

Hydrothermal remobilised deposits

These are formed by remobilisation of ore along fault planes, metasomatic replacement of host rocks or as hydrothermal deposits in veins, fissures and cracks. Host rocks vary greatly but are commonly related to an ultramafic intrusion which was the ultimate source of the nickel. These deposits tend to be lower grade and smaller in size than other classes. Important examples include the Avebury deposit, Tasmania and the Sherlock Bay deposit, Western Australia. The mineralogy can be extremely varied reflecting the different sources and host rocks but

⁴ Peridotite is a rock comprised of ≥40% olivine, with or without other mafic minerals. Serpentinisation is the process of hydrothermal alteration of minerals in the peridotite.

normally includes serpentine minerals, millerite, niccolite and, occasionally, less common minerals such as siegenite.

Manganese nodules

On sediment-starved deep ocean floors concretions rich in manganese, cobalt and nickel can form around small fragments of debris and organic material. The nodules extract minerals from siliceous oozes and from the water column. The occurrence of these nodules in proximity to mid-ocean rises suggests a volcanogenic source for mineral enrichment. They can occur as densely packed sheets and cover areas of hundreds of square kilometres. Their grades commonly lie in the range 0.5–1.3% Ni. It is estimated that the resources of nickel in these nodules 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

Depending on their size, grade and morphology, sulphide deposits are mined by either underground or open-pit methods, or a combination of both. Laterite deposits are normally mined from open pits.

Open-pit mining

Where an orebody is close to the surface (normally less than 100 m depth), open pit extraction is favoured as it is more cost effective than underground mining. This method typically involves removing the overburden⁵, digging the ore or blasting with explosives, then removing

the ore by truck or conveyor belt for stockpiling prior to further processing. An example is the Voisey's Bay deposit, Canada. Here, sulphide deposits are drilled on 5 m benches. The ore is then loaded, via wheel loaders, onto 90-tonne haul trucks and fed into a crusher. Waste rock is dumped near the pit.

Due to the clayey-saprolitic nature of laterite ores and shallow depth of the deposits, strip mining may be used. The overburden is removed and deposited in the hole left from the excavation of the previous strip, and the ore can be simply dug out.

Underground mining

Underground extraction uses a variety of standard mining methods depending on the characteristics of the mineral deposits. An example is the komatiite-based Raglan mine, Canada, where, in active workings 30 m wide and 105 m long, a mechanised cutter works 8–10 m-wide 5 m-high panels. All workings are backfilled using waste materials.

In the Zapolyarny mine, of the Noril'sk mining district in Russia, panels 12 m wide and 30–60 m in length are undercut and drilled, and then brought down using explosives. This material is then extracted and loaded onto an underground rail system that transports materials to the crushing mill.

Opencast and underground mining 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. Examples of mines using this combination are the sulphide deposits at Sally Malay in Western Australia, and at Raglan in Quebec, Canada.

⁵ Overburden is the material, such as soil, sand, clay etc., that lies above a mineral deposit.

Processing

After mining, nickel ores (1–4% Ni) are further processed to upgrade their nickel content. The resulting concentrates typically have nickel content in the range 10–20%. Concentration is normally carried out at, or close to, the mine site and involves crushing the ore and separating nickel-bearing and gangue⁶ minerals, using suitable physical and chemical processes. Smelting and refining may be carried out at or near the mine, or ore may be transported or exported for processing to metal. Pyrometallurgical or hydrometallurgical processes may be used in processing ores, although different procedures may be preferred in processing magmatic sulphide ores and laterite-hosted ores due to their chemical and textural differences.

Sulphide ores

Sulphide ore, typically containing chalcopyrite, pyrrhotite and pentlandite, is fed into a primary crusher, and then undergoes one or more stages of secondary crushing. At each stage vibrating screens allow material of the appropriate size to pass on to the next part of the processing circuit. The purpose is to maximise separation of the ore minerals from the gangue without over-milling, due to the high cost of this process. The particles containing pyrrhotite are magnetically separated and removed for further processing in order to maximise nickel recovery through removal of iron-rich pyrrhotite.

The crushed ore is mixed with water to create a slurry which is fed into a series of grinders until a powder of the required grain size is produced. Following grinding, additional water is added to the powdered ore to produce a suspension and air is blown upwards through the tanks. Chemicals are added to the mix, making some minerals water-repellent and causing air bubbles to stick to their surfaces. Consequently, these minerals collect in froth at the surface and are removed. The first stage of froth flotation is designed to remove copper concentrate, if present. The second stage of froth flotation produces a nickel concentrate which, after dewatering in thickeners and filters, contains approximately 10–20% Ni, and various other by-product metals and gangue minerals.

The next stage in production of nickel metal is smelting. The purpose of smelting is to recover as much metal as possible from the concentrate. Flash smelting is

commonly used, where dry concentrates are fed into the furnace with a preheated air, oxygen or mixture. The exothermic reaction produces enough heat to smelt the concentrate and produces liquid matte and slag. Nickel and cobalt are recovered as a sulphide matte, containing up to approximately 70% Ni; iron is recovered in slag and sulphur in sulphur dioxide.

Two basic processes are used in refining: pyrometallurgy and hydrometallurgy. In pyrometallurgy, heat is used to separate the metal from the other constituents of the matte using differences in melting points, densities and other physical and chemical characteristics. In hydrometallurgy, metals are separated using differences in solubility, and electrochemical properties while in solution.

In the hydrometallurgical ammonia leach process, nickel is leached from the matte using ammonia under high pressure. This produces a nickel-bearing solution, which is treated to remove copper, and then with hydrogen gas under high pressure to precipitate nickel metal. If any nickel remains in the solution it may be precipitated using hydrogen sulphide.

Other leaching processes use chlorine or acid leaching under atmospheric conditions. After leaching the metal is recovered by electrowinning. Electrowinning involves passing a current from an inert anode through the leach solution with nickel deposited onto the cathode. The choice of leaching process depends on factors such as impurities in the matte, the cost of energy and whether or not there is an acid plant on site producing sulphuric acid from metal sulphide smelting (see Riekkola-Vanhanen, 1999, for more detailed information and comparison of techniques).

A recently developed process, Activox[®], uses a combination of established procedures and enables the smelting step to be removed. Ultra fine grinding and pressure oxidation of the concentrate in an autoclave precede a series of solvent extractions and metal precipitations. Nickel is finally extracted through electrowinning in electrolytic cells.

Bioleaching has the potential to be used on low-grade ores and may be used for reworking waste dumps. Several companies are involved in research to improve this technology.

⁶ Gangue describes the minerals in an ore that do not have economic value.

Bioleaching under atmospheric pressure is a new technology being applied to the extraction of nickel. It is being used in the Talvivaara project in central Finland, Europe's largest known sulphide mineral resource (340 Mt at 0.27% Ni, 0.56% Zn, 0.14% Cu and 0.02% Co (Mining Magazine, June 2007)). The leaching process has been tested in a pilot operation, using bacteria endemic to the area. Ore will be mined from two large open pits in different deposits, and ground to 80 per cent passing 8 mm before being stockpiled. The ground ore will then be agglomerated and coated with sulphuric acid in a rotary drum. From here it will be transported to the plastic-lined primary, then secondary, leach pads. The leach pads will be supplied with air and nutrients via piping under the heaps in order to keep the bacteria alive and to maximise productivity. The leach solution, which is acidic and also contains bacteria to aid the leaching process, will be used to irrigate the heap from the top using plastic pipes. The leach solution will be pumped to the processing plant for the precipitation of metal sulphides. These are filtered to provide saleable concentrates and the leach solution is purified and reused.

Lateritic ores

Silicate lateritic ores which comprise mainly saprolite and garnierite are best suited to pyrometallurgical processes. The dried ore is smelted in an electric furnace at around 1600°C with carbon as a reducing agent. If matte (see p.10) is required, sulphur is also added to this process. Further refining to produce ferro-nickel or matte completes this process. This is an energy intensive process, requiring heat to remove free moisture and combined water in addition to calcining and smelting.

Two hydrometallurgical methods are used in processing limonitic (oxide) lateritic ores: the Caron Process and Pressure Acid Leaching (PAL). The older Caron process involves selective reduction of the ore and ammonia leaching. It can be used to process ores with higher levels of magnesium than PAL but it is more energy intensive as it includes drying, calcining and reduction stages, and recovery of metal is lower.

PAL involves preheating the slurried ore and leaching, usually in a titanium-lined autoclave, with concentrated sulphuric acid at high temperature and pressure. After about

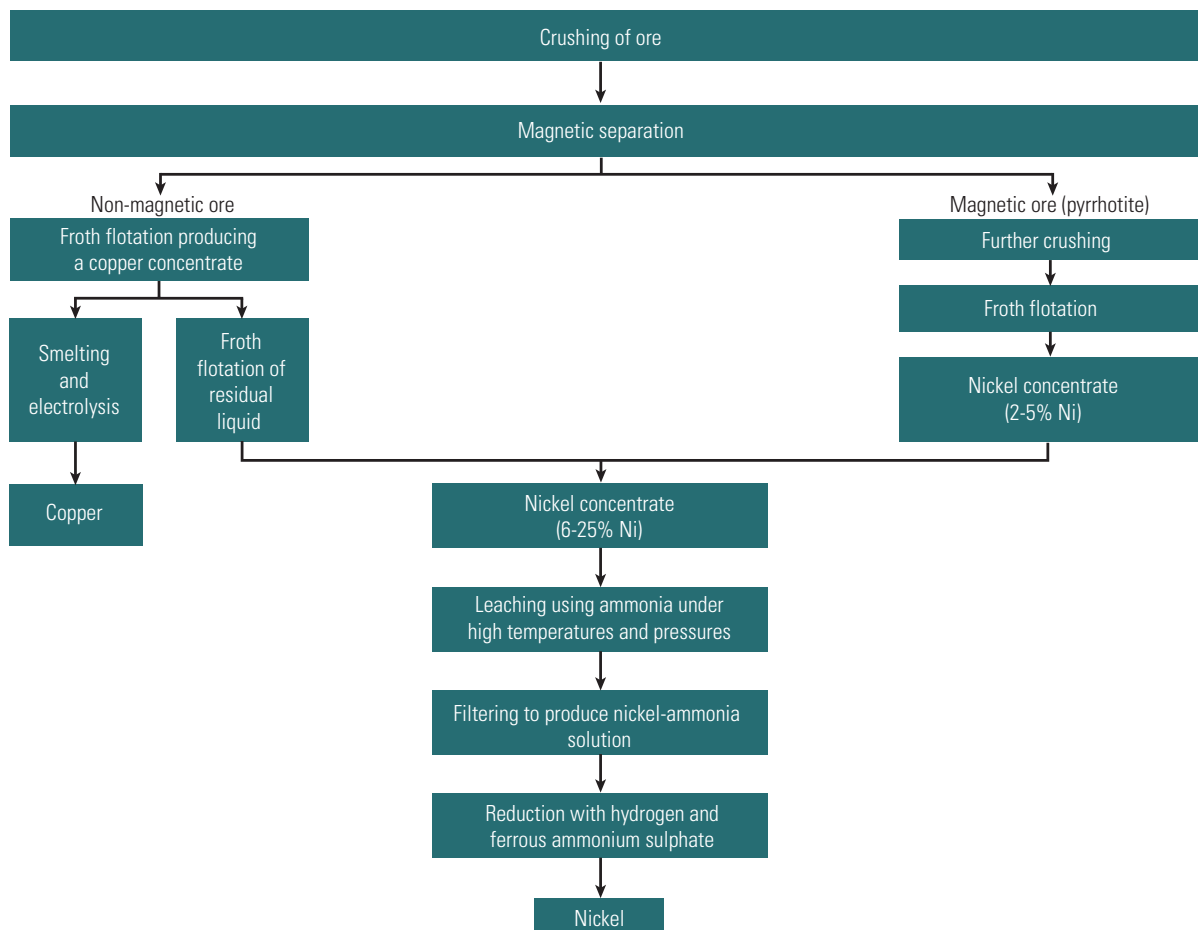


Figure 1 A flow sheet summarising typical processing of magmatic sulphide ores.

90 minutes at 255°C and 44 bar pressure, the nickel and cobalt are converted to soluble sulphate salts which are recovered from the slurry in a counter-current decantation circuit (CCD). CCD involves several stages of washing the residue and recovering soluble nickel and cobalt in the liquid. The remaining acid in this liquid is neutralised using a limestone slurry, producing a gypsum precipitate. Nickel and other sulphides are precipitated in the next stage, through a reaction with injected hydrogen sulphide. This mixed metal sulphide is refined through re-leaching with oxygen at high pressure, then removing iron and copper using chemical reactions with ammonia and air, and sulphide, respectively. Anhydrous ammonia and ammonium sulphate are added to the preheated nickel solution, hydrogen is introduced under high pressure and nickel is precipitated. PAL is most suitable for ores low in magnesium and aluminium as high levels increase acid consumption. Figure 2 summarises these processes.

Vapometallurgy is another process that is effective for processing lateritic ores. Nickel metal can be recovered and refined directly from the ore, matte or concentrate.

The metal in the ore is vaporised chemically to nickel tetracarbonyl using carbon monoxide and other gases. This vapour then passes to a separate chamber where metal is deposited as powder or other forms. This is a streamlined process which mainly operates at atmospheric pressure.

European Nickel plc has been running trials on sulphuric acid heap leaching in their Çaldag deposit, Turkey. The nickel in the lateritic ore is held in goethite which is soluble in dilute sulphuric acid. The low clay content of the laterite is advantageous as this permits percolation of the solutions through the heaps. The leaching mechanism and duration of the process vary depending on the mineralogical characteristics of the laterite. The pregnant leach solution is collected in ponds and recirculated through the heaps to maximise the metal content. It is pumped to the precipitation plant where first the iron content is precipitated by raising the pH level. This is disposed of as waste. The pH of the remaining solution is further increased using soda ash to produce a nickel-cobalt hydroxide (Ni > 30%) which is sold for refining.

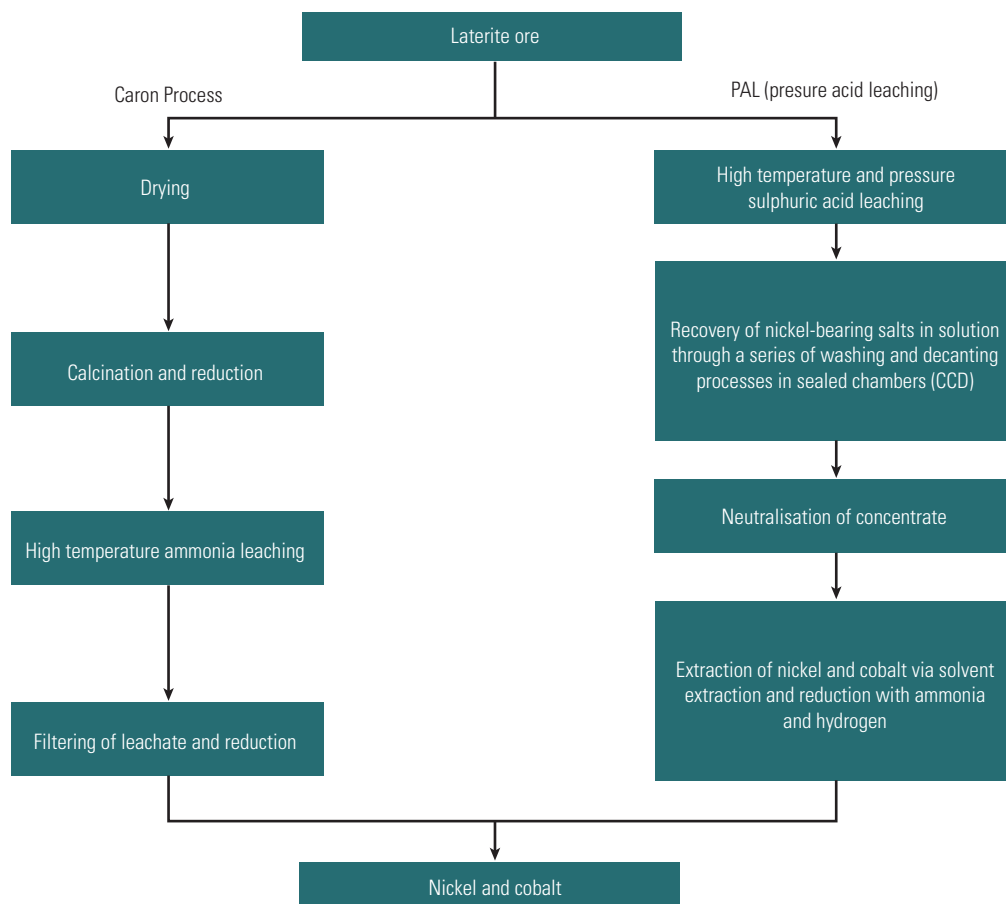


Figure 2 A flow sheet summarising the processing of lateritic ores.

Specification and uses

Nickel is produced in a wide variety of forms. The chief of these are as follows.

Specification

Nickel matte

Nickel matte is an intermediate product of nickel metallurgy which is used in the preparation of refined metal. It is produced in smelters and comprises a mixture of nickel and iron sulphides. Some other metals, such as copper, may also be included. Matte usually contains approximately 70% Ni.

Nickel oxide sinters

This is a material produced in smelters to specifications used by the steel industry. Grades range from 74–90% Ni.

Refined nickel metal

In the Harmonised System (HS) of trade codes, unwrought nickel is defined as at least 99% Ni. Cobalt does not exceed 1.5%, iron must be less than 0.5%, oxygen less than 0.4% and other elements must each be less than 0.3%. This includes electrolytic nickel.

Nickel alloys

Nickel alloys contain more nickel by weight than any other metals contained in the alloy. According to the HS system, the content of cobalt, iron or other elements must exceed the percentages given for refined nickel metal, above.

There are many nickel-based high-performance alloys used in a variety of applications, such as components in



High purity nickel crowns, produced at the Nikkelverk refinery, Norway. Courtesy of Xstrata Plc.

⁷ Trade names.

chemicals and aerospace industries, heat exchangers and missile components, that rely on nickel's properties of corrosion resistance, ductility, thermal conductivity and performance at high temperatures. These include the Monel alloys⁷ (70% Ni), the Inconel group⁷ (60–76% Ni), Ni-Cr alloys (77% Ni), and the superalloys (50–80% Ni).

Unwrought Cu-Ni or Cu-Ni-Zn alloys contain around 25% Ni, and iron-nickel based alloys, have 20%–35% Ni.

Ferro-nickel

Ferro-nickel is an alloy normally produced by direct smelting of lateritic ore. It contains 20–38% nickel, although the higher grades are more usual.

Chemicals

Numerous nickel chemicals are marketed, including acetate, carbonate, chloride, oxide and hydroxide, and sulphate.

Nickel pig iron

Nickel pig iron is a ferro-nickel pig iron containing only 3–5% nickel and higher concentrations of sulphur and phosphorus than ferronickel. Nickel pig iron is produced from low grade laterite ores. It can be used to produce the low-nickel 200-series stainless steels, and has limited application to the widely-used, nickel-bearing 300-series at present, with the potential for increased use if there are technological improvements.

Uses

Nickel is a versatile metal that readily forms alloys suitable for numerous applications. Nickel-bearing alloys are most valued for their corrosion resistance, high melting point, ductility, malleability and magnetic properties. Figure 3 shows that around 80 per cent of first-use nickel (excludes recycled nickel) is alloyed.

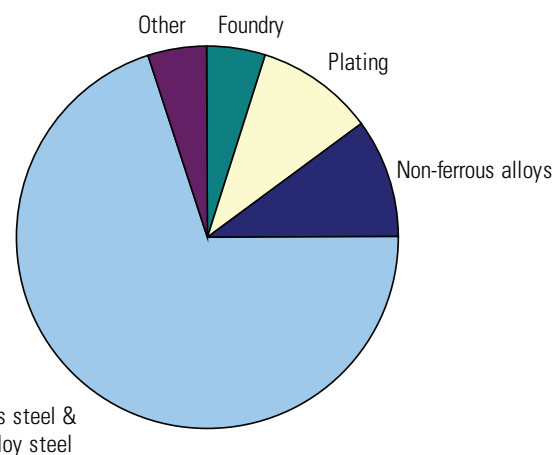


Figure 3 World use of primary nickel.



Stainless steel cutlery. © Ingram Publishing.

Stainless steel

Nickel is used in steel to increase its strength, toughness and ability to be hardened. A carbon steel structure changes on cooling from austenitic (a solid solution of iron and alloying element) to a mixture of ferrite⁸ and cementite⁹. Addition of nickel (8–10%) to high chromium (17–25%) stainless steel prevents this happening and results in the most important class of corrosion and heat-resistant steels. These have superior ductility, lower yield stress, and higher strength at both high and low temperatures than a normal carbon steel and are suitable for use in hostile environments such as marine, chemical and hydrocarbons industries. Nickel prices can impact significantly on the cost of producing stainless steel, but substitutes such as carbon, manganese, nitrogen and copper are less effective.

The largest use of nickel is in stainless steel which is used for a wide variety of purposes. As it is easy to clean and corrosion resistant it is commonly used in cutlery, food preparation, washing and medical apparatus. It is often used for mechanical applications, such as cladding for pipes and valves, and also for the transport, chemical processing and construction industries.

Other steel alloys

About 10 per cent of nickel is used in other steel alloys. Nickel is an important addition to cast iron in which it improves the hardness, malleability and closeness of grain.

Nickel-iron alloys also have very useful low expansion characteristics which makes them well suited for liquid gas storage where low temperatures are required. This is

a rapidly growing application due to the UK's increasing dependence on natural gas imports.

Non-ferrous alloys

Around 12 per cent of nickel is used in non-ferrous alloys. The most common is cupronickel, a Cu-Ni-Fe-Mn alloy, which is used extensively in coins as it is resistant to corrosion. The electrode potential of cupronickel can be adjusted so it is stable in seawater and can be used for marine applications and desalination plants.

Nickel alloys may be used to clad or line components for corrosion resistance. An example of this is in covering the inside of flue gas desulphurisation units in coal-fired power stations.

Nickel-titanium memory alloys are examples of modern non-ferrous alloys useful in specific applications. These alloys can revert back to their original shape without undergoing plastic deformation under stress. One of their best known uses is in spectacle frames. Another developing area of use for non-ferrous nickel alloys is in batteries. Nickel-cadmium rechargeable batteries are well known, but modern nickel-metal hydride batteries, using nickel-rare earth alloys, have been developed with the capacity to store hydrogen. These are used in various devices such as portable computers and cordless power tools.

Nickel also forms the base of many superalloys which are specialised alloys vital for power generation, aerospace and military applications, and mainly for the production of turbines.

⁸ Ferrite is a soft and ductile phase of steel which can hold only a minimal amount of carbon.

⁹ Cementite is a compound of iron and carbon that is hard and brittle.

Nickel superalloys can increase energy production from turbines in power plants by up to 18 per cent by improving turbine performance. In these turbines, crystalline nickel phases can stop creep in the metal caused by the high temperatures and forces acting upon it.

Plating

In plating, nickel is applied in a thin layer using electrolysis or from a solution without using an electric current (electroless). This has wide applications in corrosion resistance (important for medical equipment and construction materials) and cosmetic applications (e.g. cutlery and domestic fittings). Computer hard discs are reliant on electroless nickel plating as a coating provides a stable uniform non-magnetic base for the magnetic recording layer. Another important use is in nickel electroplating of CD and DVD masters. CDs are made using electroformed nickel moulds. Electroforming is a nickel plating process for accurate replication of complex shapes and surfaces.

Other

Nickel is used as a catalyst in a wide range of chemical processes, including hydrogenation of vegetable oils, reforming hydrocarbons and production of fertilisers, pesticides and fungicides. The magnetic properties of nickel are utilised in electronics, for example in electromagnetic shielding of computers. Foundry products include nickel castings for pumps, valves and fittings.

World nickel resources

About 40 per cent of world nickel resources are in magmatic sulphide deposits and around 60 per cent are in laterites (Hoatson et al, 2006). The magmatic sulphides can be further divided into 50 per cent in stratabound deposits, 32 per cent in basal deposits and 18 per cent extrusive ultramafic rocks. It is estimated that a further 290 million tonnes of nickel is contained in deep sea nodules, so this could double the current estimated global nickel resource if they became economic to extract.

Country/region	Resource (Mt) magmatic sulphides	% of world total magmatic sulphides	Resource (Mt) laterites	% of world total laterites	Total Ni resources	% of world total
New Caledonia			37	22.9	37	14.1
Australia	13	12.8	21	13.1	34	13.0
Africa	19	18.3	13	8.1	32	12.0
Canada	28	28.1			28	10.8
Philippines			28	17.4	28	10.7
Russia	28	27.2			28	10.5
Indonesia			25	15.8	25	9.5
Central & South America			17	10.6	17	6.5
Caribbean			11	6.9	11	4.2
USA	8	7.9			8	3.1
China	6	5.4			6	2.3
Asia & Europe	0	0.2	5	3.3	5	2.0
Other Australasia			3	2.0	3	1.1
Total	101	100.0	161	100.0	262	100

Table 4 Proved and inferred resources taking into account the total ore inferred within individual ore bodies and the grade of the ore bodies (Hoatson et al, 2006, Dalvi et al 2004). (Totals may not add up due to rounding.) Economically recoverable reserves are much lower and subject to change, depending on the price of nickel and cost of extraction.

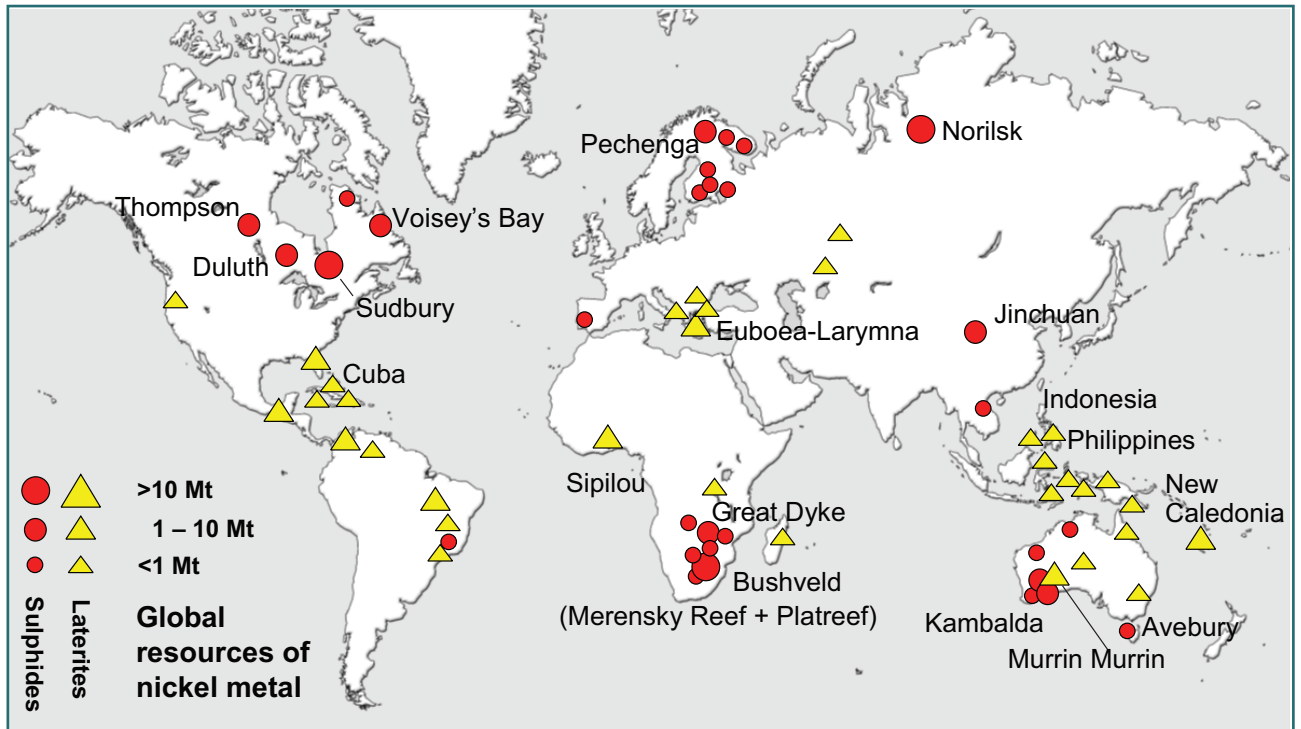


Figure 4 The global distribution of significant laterite and sulphide nickel deposits. Adapted from Hoatson et al 2006.

World production

In 2007, world production of mined nickel was 1668 thousand tonnes (nickel content of concentrates). This is an increase of nine per cent on 2006 and an increase of 25 per cent since 2003. Russia is the largest producing country with production estimated at 350 thousand tonnes.

In total, 21 countries mine nickel, the most recent addition being Spain, in 2005, with production from the Aguablanca nickel-copper-PGM mine, near Seville. Aguablanca was the first nickel sulphide mine in production in Western

Europe. Russia, Canada, Indonesia and Australia all contributed more than 10 per cent of world production. Of these, Russia, Canada and Indonesia show increases in production over five years, while Australian production has fallen slightly.

Although a higher proportion of production was from sulphide deposits, this situation will change due to the development of many major new laterite deposits, such as the Goro deposit in New Caledonia, and it is predicted that laterite production will overtake sulphide production by 2009.

World mine production of nickel, 2007
1668 thousand tonnes

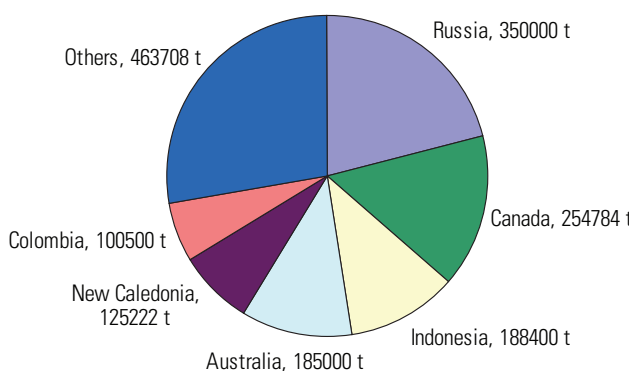


Figure 5 World mine production of nickel (content of concentrates) 2007. Source: World Mineral Production 2003-07 (in prep).

World smelter/refinery production of nickel, 2007
1426 thousand tonnes

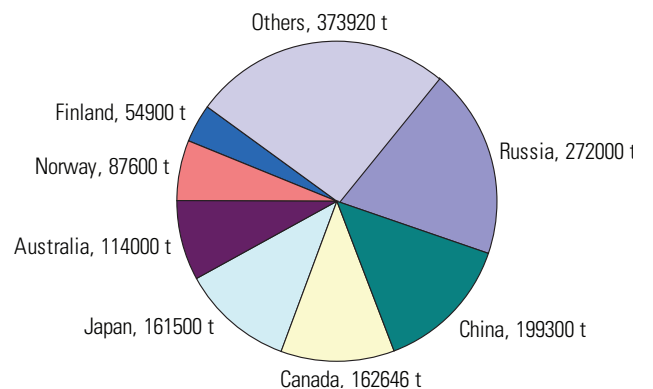


Figure 6 World production of nickel metal, 2007. Source: World Mineral Production 2003-07 (in prep).

Russia produces 19 per cent of total world output of nickel smelter and refinery products (metal and nickel content of ferro-nickel, nickel oxides and salts), and is the largest producing country. Production in Russia has increased by five per cent since 2003. Japan and China also have a significant output, reflecting their strong industrial sectors and substantial imports of concentrates and intermediate products. Between 2003 and 2007, nickel metal production in China trebled. Since 1990, world mine production of nickel has increased by 83 per cent, and

production of smelter/refinery nickel by 58 per cent (Figure 7). Consumption in 2006 attained record levels, which continued into the beginning of 2007, although the high price of nickel led to reduced usage in high nickel-content stainless steels. The highest increase in consumption was from China, from 132.8 to 327.8 thousand tonnes between 2003 and 2007, (WBMS, 2008).

Table 5 lists some of the major nickel-producing companies in 2005.

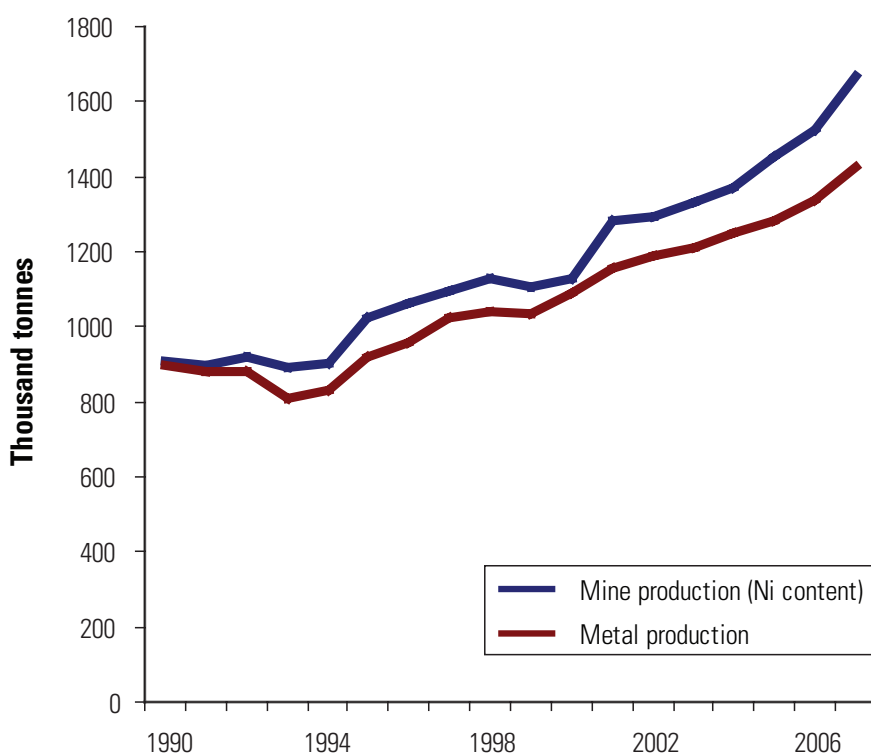


Figure 7 Production of nickel, 1990-2007. Source: World Mineral Statistics database (British Geological Survey).

Company	Mine production, Ni content (tonnes)
Norilsk	243 000
Inco (CVRD)	223 811
BHP Billiton	174 900
PT Antam	80 000
Cubaniquel	75 000
Jinchuan	71 000
Falconbridge (Xstrata)	64 002
Eramet	59 576
Anglo American plc	47 400
Votorantim Metals Ltda	22 000

Table 5 Major nickel mining companies, 2005. Source: BHP Minerals Companion.

World trade

Nickel is traded in many forms, generally as ores, concentrates, intermediate products (mattes, sinters and oxides) and unwrought metal. Nickel world trade is complex. Currently, significant quantities of mattes from Canada are processed in the UK and Norway. Ores from the Indonesia and the Philippines are processed in Japan and Australia. Mattes from Cuba are processed in Canada and mattes from New Caledonia are processed in France. Nickel imports are principally driven by stainless steel production and this is reflected by the fact that countries

with high levels of industry have the highest levels of imports, these being Western Europe, Japan and China.

The Philippines, Indonesia and New Caledonia dominate world exports in ores, concentrates, and intermediate products (Figure 8), while Japan and China are the main importing countries (Figure 10). Russia is the largest exporter of nickel metal and alloys, with 2006 exports of 260 thousand tonnes (Figure 9), more than double the exports of Canada, the second largest exporter. Imports of metal are more evenly spread, the USA being the largest importer with 131 thousand tonnes in 2006 (Figure 11).

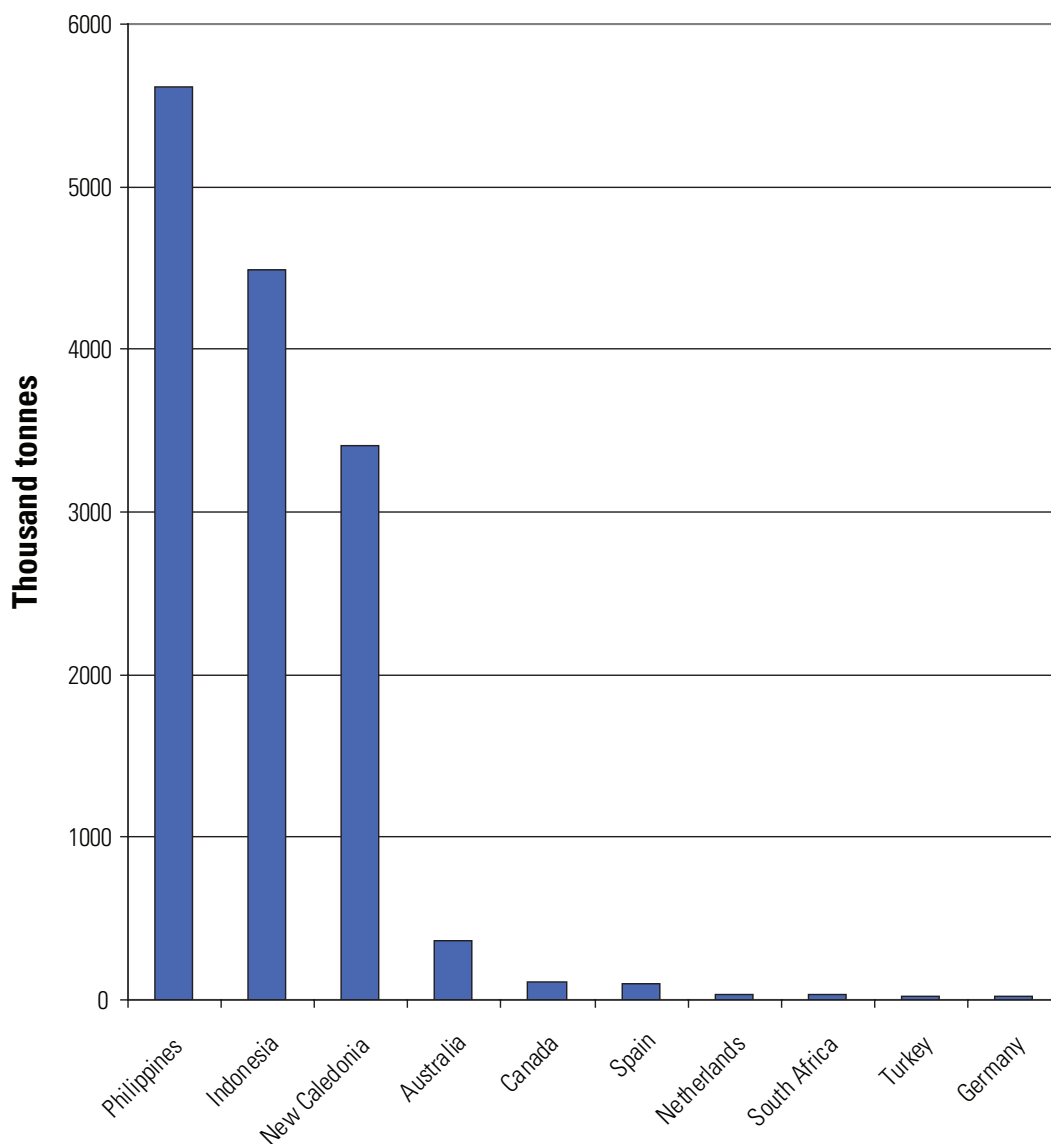


Figure 8 Major exporters of nickel ores, concentrates and intermediate products, 2006. Source: World Mineral Statistics database (British Geological Survey).

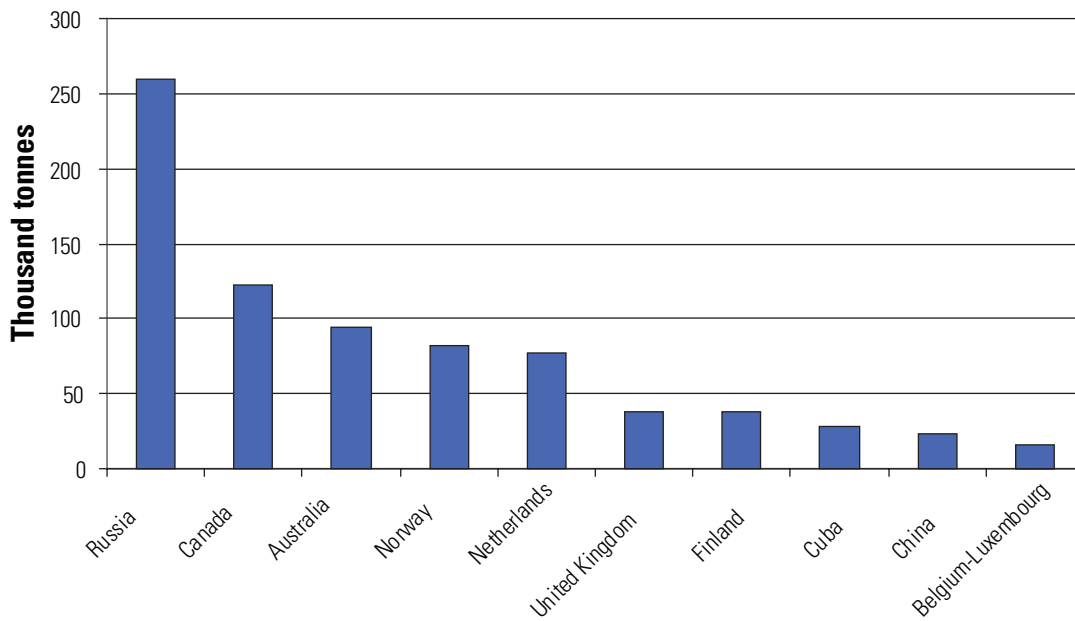


Figure 9 Major exporters of unwrought nickel and unwrought nickel alloys, 2006. Source: World Mineral Statistics database (British Geological Survey).



View of the Nikkelverk refinery, Norway. Courtesy of Xstrata plc.

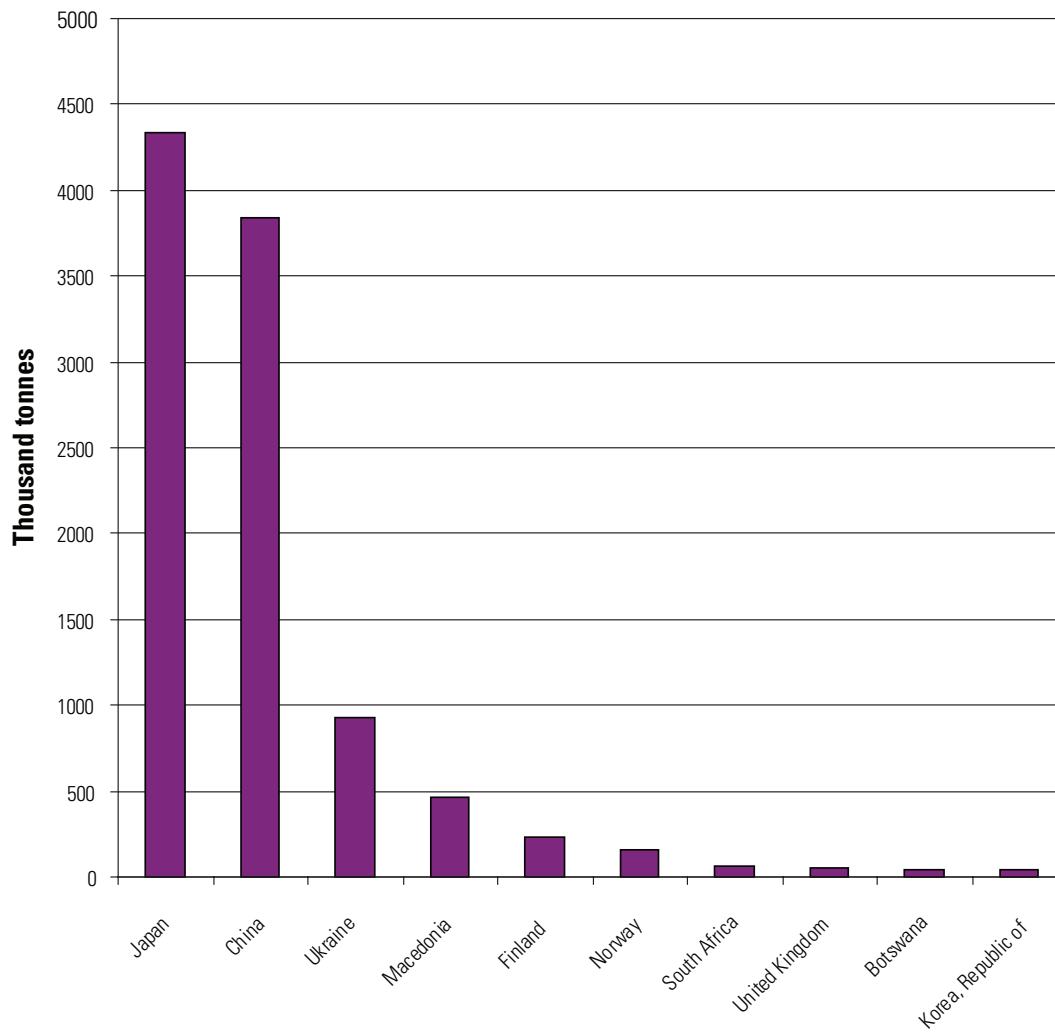


Figure 10 Major importers of nickel ores, concentrates and intermediate products, 2006. Source: World Mineral Statistics database (British Geological Survey).

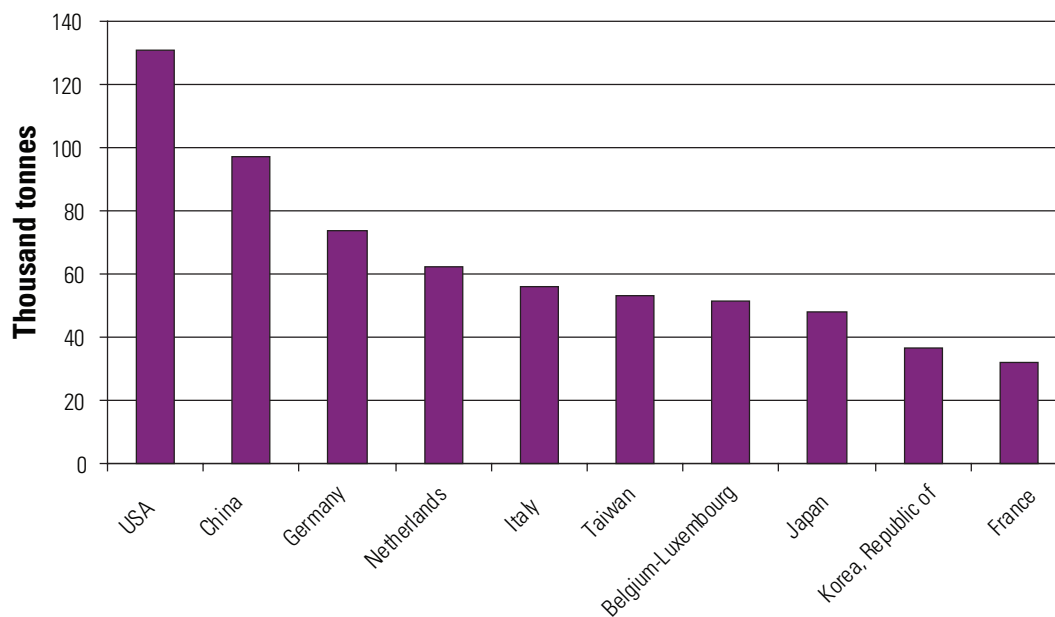


Figure 11 Major importers of unwrought nickel and unwrought nickel alloys, 2006. Source: World Mineral Statistics database (British Geological Survey).

Prices

Nickel is traded like most base metals with consumers having fixed contracts with producers. These contracts are based on the 'official' price as defined by the London Metal Exchange (LME). Nickel is rarely traded with spot prices on the open market.

Historically nickel prices have been volatile and highly susceptible to changes in supply and demand. This, coupled with nickel's historical status as a 'strategic' metal, has led to several sharp price increases over the last 30 years. The largest was the nickel boom of the late 1960s where prolonged strikes at the Sudbury Mine (one of the largest global producers) combined with increased demand led to high nickel prices and a great increase in exploration, especially in Australia.

A similar situation occurred in 2007. A global nickel shortage was caused, apparently through the increased

demand for nickel in the production of stainless steel and other alloys coupled with decreased production at Sudbury and elsewhere through strikes and delays in several major new nickel laterite operations. Inventories in LME warehouses fell to critical levels. As a consequence, prices reached a record high of US \$ 51 800 per tonne in mid-May.

By the end of 2007, prices had fallen by almost 50 per cent, to US \$ 26 000. The high price of nickel in May led to buyers of austenitic stainless steels to seek alternatives, including ferritic steels and lower nickel steels. Production of nickel pig iron (a lower grade of metal than ferro-nickel) commenced in China, boosting substitution and reducing demand for stainless steel. Higher stockpiles later in May led to prices falling, and in June, suspecting collusive behaviour in nickel trading, the LME intervened by tightening the lending rules to reduce the amount of nickel that holders can control before they are required to lend metal back to the market.



Figure 12 Nickel price (LME daily official, US \$ per tonne) January 2002 to July 2008. Courtesy of Metal Bulletin (www.metalbulletin.com).

Alternative technologies

Due to the unique properties of nickel, especially in alloying, there are very limited options for substitution. Stainless steels and other nickel-containing alloys can be substituted with plastics, and nickel content may be reduced by using nickel-coated steel rather than stainless steel. However, any substitution results in a reduction in performance. Nickel consumption can be reduced by decreasing the use of stainless steel, for example in the construction and engineering sectors, where other building materials can be used, although this greatly affects the style and aspect of the structure. It is possible to replace some super-alloys with ceramics in certain applications at a reduced cost although this is still at a research level.

The dramatic increase in nickel price in 2007 saw many steel producers move towards lowering their nickel usage. This has been achieved by converting low-grade laterite ore to nickel pig iron — a low grade alternative to nickel metal. Unfortunately, this has a higher environmental impact than the production of refined nickel. Many steel producers are also switching to production of low-nickel alternatives with higher chromium and manganese contents.

Recycling

The corrosion resistance of nickel makes it suitable for recycling and its high price provides a significant incentive

for this. Special alloys are recycled as the same alloy wherever possible, but in practice the alloys and products may get mixed.

Stainless steels are the main use of nickel. The refining processes used in producing stainless steel may include the use of recycled material, including steels, high-nickel alloys, mixed turnings, waste from primary nickel producers and re-melted ingot from processing nickel-containing slags, dusts, batteries etc. Blending processes are used to maintain quality.

Scrap metal is more often sorted according to its substrate alloy, and the nickel content would not, in this case, be treated as scrap nickel. A very small increase to the nickel content of steels would not normally cause detrimental effects.

In September 2006, the European Commission published the Batteries Directive. This Directive aims to ensure that around half of all used batteries are collected and sets efficiency targets for the reprocessing of materials, including nickel, from the spent batteries in a bid to prevent environmental and health problems. Cadmium batteries are defined as hazardous waste so a collection target of 80 per cent of all nickel cadmium batteries was set to ensure that they do not end up in the waste stream. The new strategy will create a closed-loop system for all batteries, avoiding incineration of used batteries or disposal in landfill sites.

Focus on Britain

Traditionally, nickel extraction in Britain has been as a by-product of copper and other metals, and restricted to a few localities in Cornwall and Scotland. However, the cycle of nickel booms from the late 1960s to the present day, combined with a continuous demand for steel and new ore deposit models, has led to renewed interest in Britain's nickel potential. The main focus has been concentrated on large intrusive bodies in north-east Scotland where several extensive exploration programmes have been undertaken.

The only nickel occurrences in south-west England are related to hydrothermal vein deposits in the St Austell granite. Small amounts of millerite and niccolite, and associated cobalt and uranium minerals, have been extracted from late 'cross-course' mineralisation cutting earlier tin-copper veins in a few mines. The chief producer was St Austell Consols where 126 tons of '20 to 30 per cent nickel ore' were extracted up to 1857 (Dines, 1956).

Minor amounts of nickel minerals have been found in vein-style mineralisation associated with copper and gold at Coniston in the Lake District, the Dolgellau district of north Wales, and in the central Wales lead-zinc mining field. These are of mineralogical interest only.

Historically, small amounts of nickel have been recovered as a by-product of copper mining from the Loch Fyne and Collier-Bhraghad deposits between 1854 and 1867. Dumps of nearby copper mines such as Craignure have also been worked for nickel. These deposits are related to stratabound replacement of Dalradian metasedimentary rocks near to an extensive suite of metabasic intrusives. Nickel mineralisation has also been worked in an altered diorite sheet enriched in niccolite, pyrrhotite and pentlandite at Talnotry, in south-west Scotland, between 1885 and 1900. About 100 tons were raised, although the extracted ore never left the site. Company exploration has also been carried out over the Unst ophiolite in Shetland where nickel is associated with platinum-group metals formed from hydrothermal alteration of serpentines in the basal thrust of the ophiolite. The low-grade mineralisation is in the form of Ni-Fe and Ni-Co sulphides and arsenides. Further south, exploration on the Ballantrae ophiolite, Ayrshire, has shown narrow zones of massive nickeliferous marcasite in drill core.

The greatest potential for the occurrence of economic nickel deposits is in Ordovician mafic-ultramafic intrusions emplaced in north-eastern Scotland during the Caledonian orogeny. The mineralisation comprises pyrrhotite, chalcopyrite and pentlandite, within mafic and ultramafic cumulate rocks, with sulphur sourced from assimilation

of pyritic and graphitic Dalradian metasedimentary rocks. Several surveys carried out in the late 1960s and early 1970s have located enrichment of nickel and copper of around 0.2–0.5% in the Knock and Arthrath intrusions. Arthrath has the most economic potential with a drill-indicated resource of 17 million tonnes with grades of 0.21% Ni and 0.14% Cu and indications of platinum-group metal enrichment.

Consumption

The only nickel refinery in Britain is at Clydach, near Swansea. It is operated by Inco and processes matte from Canada.

Total consumption of nickel in the UK was 32 400 tonnes in 2006, including 13 370 tonnes consumed in steel-making. Nickel consumption has been fairly constant for some time. Since 1963, consumption of nickel in iron and steel has averaged 15 600 tonnes per year. Between 1987 and 1997, consumption was relatively high, peaking at 24 680 tonnes in 1995. Consumption in other uses has averaged 15 800 tonnes per year since 1963, but was relatively low during the 1980s and early 1990s (approximately 11 000 tonnes per year).

Steel is produced at smelters and refineries in South Wales (Port Talbot, Cardiff and Newport), Birmingham, Teesside, Sheffield, Rotherham and Halifax. Large steel mills are also located in Motherwell, Deeside and Corby.

Britain has a large aerospace industry in which nickel alloys are widely used. Research into, and production of, turbines and jet engines provide high levels of investment in the British economy.

The UK is a net exporter of nickel metal. In 2006, 20 297 tonnes of unwrought metal, including alloys, were imported and exports were 38 096 tonnes. Ferro-nickel imports were 13 169 tonnes while exports were 329 tonnes. Imports of scrap metal were 7975 tonnes and exports were 15 555 tonnes. Net imports of mattes and other intermediate products were 55 819 tonnes.



The Clydach smelter.

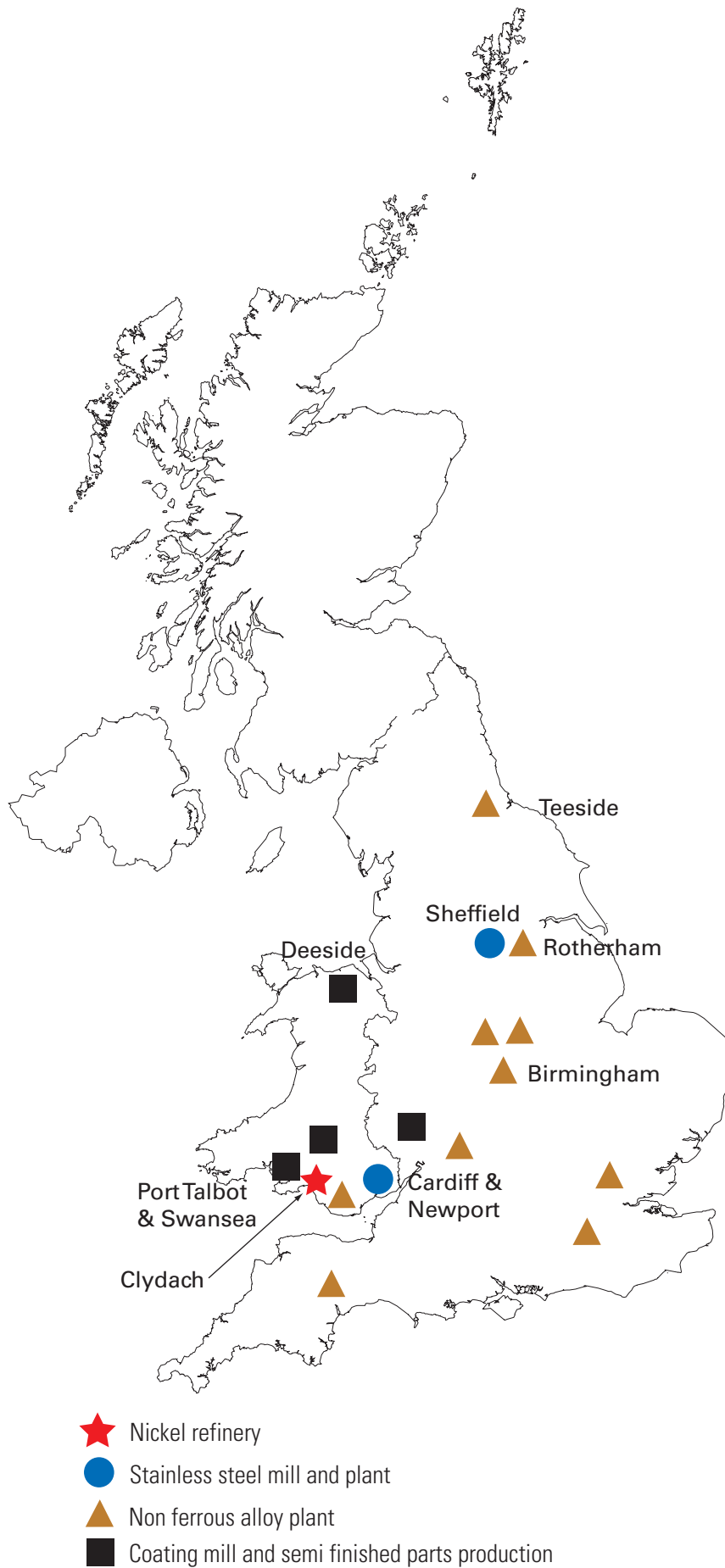


Figure 13 The nickel industry and primary use in the UK

Adapted from the European Nickel Industry Association. http://www.enia.org/index.cfm/ci_id/13002/la_id/1.htm
Refinery locations © The Nickel Institute.

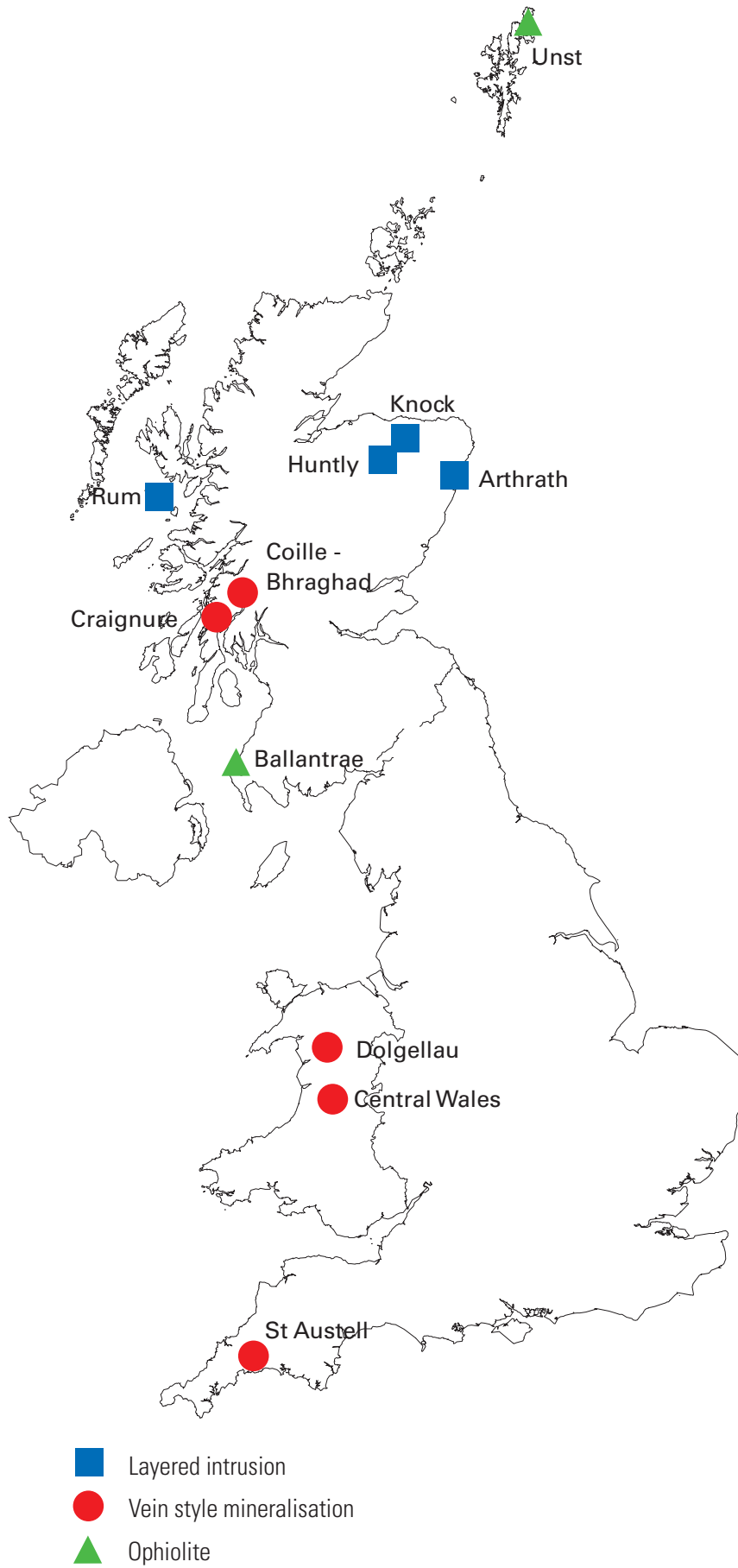


Figure 14 Locations of nickel mineralisation in the UK.

Further reading and selected references

Useful contacts for further information

European Nickel Industry Association	www.enia.org
International Nickel Study Group	www.insg.org
International Stainless Steel Forum	www.worldstainless.org
Nickel Institute	www.nickelinstitute.org
Mining Journal Annual Review	www.mining-journal.com/Annual_Review.aspx

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