

# Mineral Commodity Report 10 — Nickel

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## Discovery and Origin of Names

The name nickel is derived from the German *nickel*, meaning Satan or Old Nick's, and from *kupfernickel* for Old Nick's copper, the mineral niccolite.

Nickel was first used as an alloy, mainly in coinage; copper-nickel coins were used in Bactria 2230 years ago. The ancient Chinese produced "white copper" (paktong), essentially the same as the modern alloy nickel-silver, by smelting ores containing copper, nickel and zinc.

Nickel was first isolated in 1751 when the Swedish chemist Baron Axel Frederic Cronstedt prepared an impure sample of the metal from an ore containing niccolite. It was first prepared in relatively pure form by H.T. Richter in 1804.

Nickel has been used in electroplating since 1843, and in steel alloys since about 1889. It was first used as a base for alloys with the introduction of Monel nickel-copper alloy in about 1905.

Nickel gained commercial prominence in the late 1800s, when substantial reserves were found in New Caledonia (1865) and at Sudbury (1883), and the world's naval powers adopted nickel-bearing armour. Until about 1920, nickel markets depended upon military requirements, but following World War I, research into other potential uses substantially increased its applications in industry.

Symbol	Ni
Atomic no.	28
Atomic wt	58.69
Specific gravity	8.9
Valence	0, 1, 2, 3
Melting point	1455°C
Boiling point	2730°C
Crustal abundance	70 ppm
Preferred analysis method	plasma atomic emission spectroscopy
Routine detection limit	1 ppm

## Major Ores and Minerals

Nickel ranks about 22nd in natural abundance among elements in crustal rock, but about 5th in the earth as a whole. It is concentrated in ultramafic igneous rocks (0.1–0.3% Ni) compared with silicic igneous rocks (<0.006% Ni). The most important ore minerals are the sulphides pentlandite and pyrrhotite, and the oxide garnierite (Table 1). Other nickel minerals include niccolite, millerite, breithauptite, choanthite, gersdorffite and ullmannite. Nickel may also be present in goethite (limonite)  $(\text{Ni,Fe})\text{O}(\text{OH})\cdot n\text{H}_2\text{O}$ .

Nickel occurs as a metal in meteorites and often serves as one of the criteria for distinguishing a meteorite from other rocks. Iron meteorites, or siderites, may contain 5–20% Ni.

Name	Formula	Colour	Hardness	Density	Lustre	Crystal System	Transparency
Breithauptite	NiSb	copper-red	5.5	7.5–8.5	metallic	hexagonal	opaque
Choanthite (white nickel) (nickel skutterudite)	NiAs <sub>2</sub>	tin-white	5.5–6	6.4–6.7	metallic	cubic	opaque
Garnierite (nickel serpentine)	$(\text{Ni,Mg})_3\text{Si}_2\text{O}_5(\text{OH})_4$	green	2–4	2.2–2.8	dull	amorphous	opaque
Gersdorffite	NiAsS	silvery-white to steel grey	5	5.9	metallic	cubic	opaque
Millerite (yellow nickel)	NiS	pale brass -yellow	3–3.5	5.3–5.6	metallic	hexagonal	opaque
Niccolite (red nickel, kupfernickel)	NiAs	copper-red	5–5.5	7.8	metallic	hexagonal	opaque
Pentlandite	$(\text{Fe,Ni})\text{S}$	bronze-yellow	3.5–4	5.0	metallic	cubic	opaque
Pyrrhotite	$(\text{Fe,Ni})\text{S}$	reddish-bronze	4	4.6	metallic	hexagonal	opaque
Ullmannite	NiSbS	white to lead-grey	5–5.5	6.7	metallic	cubic	opaque

Table 1: Nickel minerals.

## Properties

Nickel is one of the transition elements in Group VIII B of the periodic table and has chemical similarities to iron and cobalt. Nickel is a silvery white, ferromagnetic, ductile, malleable, and tough metal that takes on a high polish that does not tarnish easily. It is moderately hard (3.8), has a specific gravity of 8.9, and is a fairly good conductor of heat and electricity. The properties of the main nickel minerals are summarised in Table 1.

## Formation

Nickel occurs in four principal deposit types, of which two are currently of economic importance: magmatic sulphide ores currently contribute about 65% of world nickel production and lateritic ores most of the remaining 35%. Few hydrothermal deposits are now mined and seafloor manganese nodules have never been mined.

### Magmatic sulphide deposits

These deposits are formed by the concentration of nickel sulphides during the crystallisation of mafic and ultramafic magmas. Iron, copper, cobalt and the platinum group metals usually accompany the nickel and are by- or co-products in some deposits. The main minerals are pyrrhotite, pentlandite, chalcopyrite and magnetite. Detailed classifications of these deposits are described by Naldrett (1981, 1989), but for this review three classes are recognised: stratiform complexes, komatiite deposits, and intrusions related to flood basalts.

**Stratiform complexes:** This class includes the world's largest economic nickel deposit, the Sudbury Igneous Complex in Ontario, Canada. Sudbury has combined production and reserves of 700 Mt at 1.6% Ni and 1.3% Cu, in numerous deposits clustered in five main areas. The complex is a 60 x 27 km layered lopolith, of predominantly noritic composition, formed by a number of unusual events, including the impact of a meteor. Examples of other more conventionally formed and less economically attractive nickel deposits in stratiform complexes are in the Stillwater complex (USA) and the Bushveld complex (South Africa).

**Komatiite deposits:** In these deposits, nickel-bearing sulphides occur at the base of ultramafic (komatiite) flows and sills formed in Archean and Proterozoic greenstone belts. Spinifex textures are a notable feature in parts of the flows. The ore bodies range from less than 1 Mt up to 5 Mt and commonly several ore bodies may constitute a single deposit. Typical grades are 1–5% Ni and 0.1–0.25% Cu, with Cu/Ni ratios of 10–20. Important deposits occur in the Precambrian shield areas of Australia (Eastern Goldfields district), Canada (Abitibi and Thompson districts) and Zimbabwe.

**Intrusions related to flood basalts:** These deposits are formed in mafic intrusions associated with tholeiitic flood basalts in continental rift zones. Cu/Ni ratios are 2–0.7 and (Pt + Pd)/Ni ratios are around 0.002. The main examples are deposits in the Noril'sk-Talnakh region (northern Siberia, Russia) and the large, but subeconomic, Duluth complex (Minnesota, USA).

## Laterites

The first significant nickel production in the world was from mining laterites in New Caledonia from 1876. Nickeliferous laterites are residual deposits formed by intense tropical weathering of ultramafic rocks, such as peridotites and serpentinites, that contain 0.2–0.3% Ni held in olivine (Golightly, 1981). The released nickel is moved by ground water until increases in pH deposit it either in hydrous iron oxides (mostly goethite) or in secondary silicate minerals composed mostly of clays or serpentine minerals such as garnierite. Cobalt may also be concentrated. Profiles of typical nickeliferous laterites have a layer of iron-rich or oxide ore that contains 0.5–1.5% Ni above a thinner zone of silicate-rich or garnierite ore that typically has 1.5–3% Ni and which rests on unweathered bedrock. However, many deposits are made up mostly of oxide ore and lack significant amounts of the richer silicates. Laterite deposits are typically 2–25 m thick and contain 10–100 Mt of ore grading 1–3% Ni + Co. Important deposits occur in New Caledonia (Doniambo), the Philippines (Davao and Surigao), Indonesia (Waigo), Cuba (Nicaro and Moa Bay) and the Dominican Republic (Falconbridge). Fossil laterites are rare, but economic deposits occur in the Ural Mountains, Greece and at Riddle in Oregon.

## Hydrothermal deposits

Nickel, copper and cobalt occur either as sulphides or as arsenides in vein deposits. Although some deposits of this type were important when nickel was first being mined, most are no longer of economic interest.

## Seafloor manganese nodules

Seafloor manganese nodules, typically containing about 25% Mn, 1.5% Ni, 1.5% Cu and 0.2% Co, are abundant in sediment-starved areas of the deep ocean basins, mainly in the Pacific Ocean. They occur in irregular, single-layer fields at or within a metre of the sediment-water interface. Individual nodules are potato-sized earthy brown to bluish-black lumps with a dull lustre. They consist of one or more nuclei (shark teeth, whale ear bones, rock fragments or other nodules) surrounded by discontinuous concentric layers of metal oxides and clay.

## Uses

More than 65% of the nickel produced is used in alloys with iron and steel, about 15% is used in corrosion-resistant alloys with copper and in heat resistant alloys with chromium, 5% is used in alloy castings, and only the remaining 15% is used in unalloyed forms, either in electroplating (10%) or for various minor applications such as batteries, catalysts, magnets and ceramics.

Nickel steels contain 0.5–7% Ni in the “low-nickel steels” and 7–35% in “high-nickel steels”, nickel-irons from 0.5–15% Ni, nickel brasses and bronzes 0.5–7% Ni, copper-nickel alloys from 2.5–45% Ni, Monel metal 67% Ni, and special alloys up to 80% Ni.

Nickel is used in alloys to impart toughness, strength, lightness, and resistance to heat and/or corrosion. Nickel steels and alloys are used for moving and wearing parts of various machines, tools, shafts, bolts, axles, and gears, in automobiles,

airplanes, and ships, and in railway, power, agricultural, crushing, mining, milling and pressing equipment. Nickel silver, also called German silver, (typically 55–65% Cu, 18% Ni and the rest Zn), is used as the base for tableware, jewellery, and other articles to be silver plated. Nickel alloys are used extensively in coinage (25% Ni and 75% Cu).

Nickel metal is used to form protective coatings on other metals, particularly iron and steel, that are susceptible to corrosion. Finely divided nickel absorbs 17 times its own volume of hydrogen and is used as a catalyst in many processes, including the hydrogenation of unsaturated organic compounds such as vegetable oils and fats. Nickel is also used in the manufacture of Alnico magnets, and it is added to glass to give a green colour.

Nickel sulphate is used for electroplating and in the preparation of catalysts, ground-coat enamels, and mordants (fixatives) for dyeing and textile printing. Nickel oxide and nickel peroxide are prepared for use in fuel cells and storage batteries, respectively. Nickel ferrites are utilised as magnetic cores for various type of electrical equipment such as antennas and transformers.

Both plant and animal tissues contain small amounts of nickel. Normal human diet contains about 0.3 to 0.5 milligrams of nickel per day. If taken beyond a certain tolerance level, not yet determined with precision, nickel produces toxic effects through inhibition of certain enzyme systems.

## Price

Nickel prices are closely tied to the production of steel and iron alloys, particularly stainless steel. They were low in 1993 (US\$2.40/lb) and 1994 (US\$2.87/lb), compared with 1991 (US\$3.70/lb), but have increased to around US\$3.80/lb in early September 1995.

## World Production and Consumption

World primary nickel production is about 700,000 t/y (655,000 t for the “established market economy countries” in 1993). The main producers of refined nickel in 1993 were the Commonwealth of Independent States (160,000 t; mainly Noril’sk), Canada (118,000 t; mainly Sudbury), Japan (101,000 t), Norway (57,000 t), Australia (51,000 t), New Caledonia (37,000 t), China (29,000 t), South Africa (28,000 t), Finland (27,000 t) and the Dominican Republic (24,000 t) (Hinde et al., 1994). The Japanese production is based on feedstock imported from a number of countries including Indonesia which consequently is not featured in the former list. Total world production of refined nickel in 1994 was about 809,500 t, whereas world consumption of nickel in 1994 was 800,500 t (Anderson, 1995). About 30 percent of annual U.S. consumption is recycled.

World reserves include land-based resources of about 168 Mt of Ni and an estimated 760 Mt Ni in deep-sea nodules.

Several new projects will have a significant impact on nickel production: McCreedy East (Inco) in Ontario Canada commenced production in 1994 at 19,000 t/y Ni and 10,000 t/y Cu, and Mount Keith (Western Mining Corporation Holdings

Ltd) in Western Australia is under construction and expected to commence production in 1995 at 28,000 t/y Ni. Yakabindie (Dominion Mining Ltd) in Western Australia (22,000 t/y Ni), Loma de Hierro (Minorco Group, Jordex Resources, and Corporacion Caracas) in Miranada Venezuela (20,000 t/y Ni), and Raglan (Falconbridge) in Quebec Canada (20,000 t/y Ni, 5,000 t/y Cu) are under feasibility studies or awaiting improved market conditions.

## Ore Processing, Smelting and Refining

Sulphide ores with nickel-bearing minerals such as pentlandite and nickeliferous pyrrhotite, typically contain 1–3% Ni and varying amounts of copper. They are first crushed and ground to liberate the ore minerals and are then upgraded and concentrated by froth flotation or magnetic separation.

The sulphide concentrates, are usually oxidised by roasting and then smelted in a blast furnace to separate an iron-rich slag from copper-iron-nickel sulphide matte (75–80% Cu-Ni) which is shipped to refineries or used directly to make Monel metal. Two main refining processes are used to remove the nickel. One involves reduction smelting to metal anodes, followed by electrolytic refining, in which the nickel is deposited in pure metallic form after the copper has been preferentially removed by deposition at a different voltage and in a different electrolyte. In the second process, known as the Mond process, copper is removed by dissolution in dilute sulphuric acid, and the nickel residue is reduced to impure metallic nickel. Carbon monoxide is passed over the impure nickel, forming nickel carbonyl  $\text{Ni}(\text{CO})_4$ , a volatile gas. The nickel carbonyl is heated to 200°C and decomposes, depositing pure metallic nickel.

Lateritic oxide and silicate ores are generally mineralogically and chemically diverse and require treating by expensive and complicated pyrometallurgical and hydrometallurgical processes. The main method used is to produce ferronickel. The ore is dried and preheated under reducing conditions. The hot charge is then further reduced and melted in an electric-arc furnace, and the crude metal is refined and cast into ferronickel pigs. Hydrometallurgical refining involves the chemical leaching of the ores with ammonia or sulphuric acid solutions. The nickel salt solution thus obtained is reduced, causing the metallic nickel to precipitate out.

## New Zealand Occurrence and Resources

The occurrence of nickel in New Zealand has been reviewed by Whittle (1965), Officers of the New Zealand Geological Survey (1970), Williams (1974) and Brathwaite and Pirajno (1993). The most significant occurrence is the nickel-copper sulphide mineralisation associated with the Riwaka Igneous Complex mafic-ultramafic rocks in the Graham Valley, Northwest Nelson. Nickel sulphide mineralisation is associated with mafic-ultramafic rocks in the Cobb Valley (upper Takaka) and at Blue Mountain in Marlborough, and minor occurrences are found in mafic-ultramafic rocks of Westland, Otago, Fiordland and Southland.

Nickel minerals found in New Zealand include: annabergite  $\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ , awaruite  $\text{Ni}_{2.3}\text{Fe}$ , bravoite  $(\text{Fe},\text{Ni})\text{S}_2$ , garnierite, heazewoodite  $\text{Ni}_3\text{S}_2$ , native nickel, pentlandite, violarite  $\text{FeNi}_2\text{S}_4$  and zaraitite  $\text{Ni}_3(\text{CO}_3)(\text{OH})_4 \cdot 4\text{H}_2\text{O}$  (Railton and Watters, 1990).

**Riwaka Complex, Graham Valley:** In the Graham Valley and Skeet River areas, nickel mineralisation is present in the Riwaka Complex, a series of small layered intrusions emplaced along a tensional fault zone in marble, phyllite and biotite schist (Bates, 1989). Bates (1980, 1989) divided the complex into:

1. Diorite that is widespread as a late-stage high level intrusive suite.
2. Cumulus gabbro of restricted occurrence, emplaced as a late-stage transgressive bodies.
3. A pyroxenite-peridotite fractionation suite consisting of a plagioclase pyroxenite and pyroxene gabbro series, a hornblende-olivine pyroxenite series and a peridotite-dunite series.

The Graham Valley nickel mineralisation occurs mainly within the cumulus gabbro, where sulphide content ranges from 1–50%, characteristically with  $\text{Ni} > \text{Cu}$ . Pyrrhotite is the major sulphide, with subordinate chalcopyrite, and minor pyrite, marcasite, and mackinawite. Pentlandite is the sole nickel-bearing phase, occurring as flames and veinlets within pyrrhotite (Gill and Johnston, 1970). Weaker sulphide mineralisation, with  $\text{Cu} > \text{Ni}$ , also occurs within other suites in the complex.

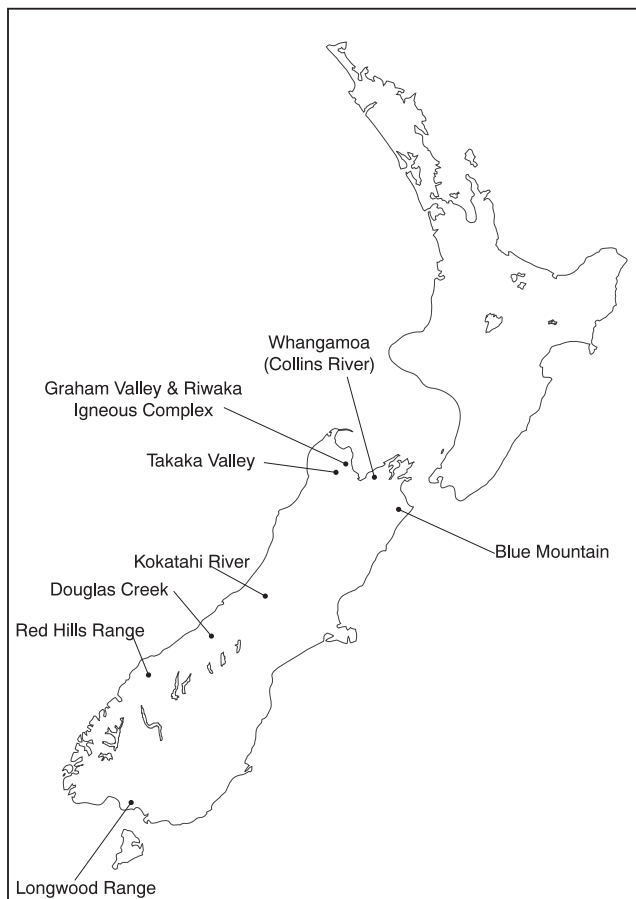


Figure 1: Location of nickel deposits in New Zealand.

Gossan, developed from nickel-copper mineralisation, was located in the Graham Valley area in 1967 (Gill and Johnston, 1967, 1970). High nickel prices at the time sparked extensive exploration of the Riwaka Complex, particularly in the Graham Valley and Pearce River. Regional stream sediment sampling by MacIntyre Mines identified nickel anomalies in Prospect Creek, Field Creek and Price's Creek. This was followed by gridded soil sampling, and magnetic and induced polarisation surveys. Twenty-six diamond drillholes were subsequently drilled on the prospects. Work was carried out by MacIntyre-Porcupine Mines (Marlatt, 1969; Purdie, 1970; Smith, 1971), Western Compass (Hutchinson, 1971), Mineral Deposits Ltd (Johnson, 1972a, 1972b), Otter (McClelland, 1976), and Gold Mines of NZ Ltd (Pirajno, 1978; Bates, 1977, 1978). Best intersections recorded from the drillholes were 2.20% Ni and 0.60% Cu over 1.4 m in hole GV19, 1.52% Ni and 0.22% Cu over 2.5 m in GV5, and 1.42% Ni and 0.42% Cu over 3.6 m in GV8 (Bates, 1989). A decline in nickel price and the sporadic distribution of the mineralisation led to the licences being relinquished in 1980. Subsequent exploration in the late 1980s has focused on platinum group elements associated with the nickel mineralisation (Cowden et al., 1988; Nicolson, 1990).

Similar occurrences were prospected further south in the Riwaka Complex in the Skeet River area, but no significant mineralisation was found (Purdie, 1971).

**Takaka Valley and Cobb River:** Lenses, veins and disseminations of gold-bearing pyrrhotite-pyrite-chalcopyrite-pentlandite mineralisation are associated with metadiorite dikes in Devil River Volcanics of the Meter Creek area, adjacent to the Cobb Igneous Complex (Henderson et al., 1959; White and Whittle, 1961; Grindley, 1962; Johnston, 1969; Smale, 1971; Hunter, 1977; Stegman, 1988). The mineralised lenses are segregations up to 3 m long and 0.9 m thick which have yielded assays of up to 4.5% Ni and 1.3% Cu in exploration work by Kennecott. Pyrrhotite is the major sulphide (>60%), with >10% associated pentlandite and minor chalcopyrite (<1%). Exploration by CRA (Stegman, 1987, 1988) concentrated on the gold potential of the mineralisation and identified several gold-copper-nickel prospects including nearby Bastite Creek. Drilling in Meter Creek gave a best intersection of 4 m of 80 ppm Ni, 1140 ppm Cu, 1.4 ppm Au and < 5 ppb Pt.

**Collins River, Whangamoia Valley, east Nelson:** Nickel sulphides have been reported in blocks in the Patuki Melange, with analyses ranging up to 0.4% Ni (Whittle, 1965; Johnston, 1969). Pentlandite occurs as isolated grains in serpentinised peridotite, along with chromite, ilmenite, bravoite, nickeliferous pyrrhotite and chalcopyrite. Elsewhere in rocks of the Dun Mountain Ophiolite Belt, nickel may be present in concentrations of up to 0.5% NiO (Williams, 1974), located in the lattice of olivine crystals or as awaruite (e.g. Red Hills; Challis and Long, 1964).

**Blue Mountain:** Nickel-copper mineralisation is associated with the Blue Mountain Igneous Complex, a central-type alkali ultrabasic-gabbro ring complex of Early Cretaceous age (Grapes, 1975) which intrudes Torlesse Supergroup rocks 15 km west of Ward, Marlborough. The complex is 1.5 km

x 1 km in area and dips steeply around the margin and more gently near the centre. Exploration by Kennecott Explorations (1971a) and Gold Mines of NZ Ltd (Pirajno, 1979) found disseminated pyrite, chalcopyrite and pyrrhotite in layered pyroxenite at three main localities. The best rock geochemical values were 1600 ppm Cu and 1300 ppm Ni. The longest strike extension of mineralisation is 750 m. Iron-, titanium-, and vanadium-bearing minerals are also present in the alkali gabbro dikes and layered olivine gabbro of a marginal zone.

**Westland:** Boulders of nephritic material containing nickel mineralisation have been found in Douglas Creek (Williams, 1974). In-situ mineralisation is present in the Pounamu Ultramafics as stratabound bands in Whakarira Gorge, on the Kokatahi River, and sporadically elsewhere as minor pyrrhotite-pentlandite-chalcopyrite, along with magnetite and chromite, disseminated in serpentinite (MacKenzie, 1984). The Pounamu Ultramafics and adjacent Haast Schists were prospected by Kennecott and CRA (MacKenzie, 1984), and anomalous nickel values were found associated with serpentinite margin metasomatism, where nickel has been depleted from serpentinite margins and enriched in marginal schists (MacKenzie, 1984).

**Red Hills Range, Otago and South Westland:** On the western side of Red Mountain and Little Red Hill, bands of pentlandite-pyrrhotite-chalcopyrite mineralisation are present in sheared serpentinites at the contact with late Paleozoic volcanic rocks. The Red Mountain occurrence consists of three bands, 0.6 m thick and up to 1 m apart, traceable for 30 m along a strike of 030° (Mutch, 1965). At the northern end of the Red Hills Range, awaruite is found in dunite-peridotite blocky serpentinite masses containing 0.1–0.5% Ni. Placer deposits of awaruite and native nickel are found in the Gorge and Jerry rivers (Mutch, 1965; Challis, 1975). Nickel Spoon Mining Company carried out geochemical surveys in the area and obtained values between 40 and 1900 ppm Ni for stream sediment samples, and between 65 and 3010 ppm for soil and rock samples (Happy et al., 1970; Rowlands et al., 1970; Hurst, 1971).

**Southland:** Ultramafic rocks in the **West Dome** area were prospected for nickel by Kennecott Explorations (1971b, 1971c, 1971d) using stream sediment geochemical surveys but the nickel concentrations were considered to be within the locally high background level for the ultramafic rocks. In the **Otama Igneous Complex**, chalcopyrite, pyrite and minor pyrrhotite are associated with sheared and brecciated zones in granophyre, diorite and gabbro (McPherson, 1973; Lay, 1976). In the **Longwood Range**, a number of weak nickel (along with Cu and Zn) stream sediment geochemical anomalies were reported by Williams (1967) and MacPherson (1970).

**Fiordland:** Pirajno (1981) described copper-nickel mineralisation in layered gabbroic rocks in the western sector of the **Darran Complex**, Darran Mountains. At Camera Lake, lenses of disseminated pyrrhotite and chalcopyrite are present in anorthosite. The two largest lenses are exposed over strike lengths of 50 m and 25 m respectively, and have thicknesses varying from 1 m to 8 m. At Falls Creek, disseminated sulphide-oxide mineralisation consists of pyrite-chalcopyrite-pyrrhotite and magnetite-hematite-ilmenite.

In **Isolation Basin**, near Lake Hauroko, a 90 m long pyroxenite dike intrudes Mt Solitary Formation and assayed 890 ppm Ni and 465 ppm Cu (Bell, 1975). Biotite semischist float in the same catchment assayed 0.28% Ni and 0.23% Cu. Pentlandite is a minor constituent in the **Mt Solitary copper lode** and in other mineralisation at Mt Solitary (Cox, 1878). Park (1888, 1924) described a 60 cm thick bed of pyrrhotite (0.68% Ni) in quartz mica schist at Mt Hodges, and also noted that nickeliferous pyrrhotite was present in **Parks Mineral Beds**, between Mt Pender and Mt Hodges.

**Stewart Island:** Nickel geochemical anomalies were reported in the Anglem Complex by Waddell (1971).

## Potential and Prospectivity

No nickel ore has been mined in New Zealand. Drill testing of the Graham Valley deposits indicated that they were too small to be economic as primary nickel deposits, but recent exploration for platinum group metals suggests that there may be potential for byproduct mining of nickel in the future if significant platinum group metal deposits are found.

Proposals have been made for smelting of laterite nickel ore from New Caledonia using low-cost electricity in New Zealand.

## Future Trends

Nickel is essential for stainless steel and other special alloys, and these will continue to be imported into New Zealand.

Foose (1989) suggested that the increased mining of lateritic ores will continue to shift production away from sulphide deposits. Sulphide ores, however, will still be important and significant discoveries are possible, particularly for the komatiitic and Noril'sk type deposits. The short term adequacy of land-based resources will slow development of the ocean-floor nodules but, pending resolution of legal and technological problems, they will eventually become a major source of nickel.

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