

Mineral Commodity Report 15 — Iron

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Discovery and Origin of Names

Prehistoric people obtained iron from meteorites and used it to make ornaments, tools and weapons. Iron beads have been found in Egypt, dating from about 6000 years ago, whereas the earliest iron implements, also in Egypt, are from about 5000 years ago. The first processed iron was probably obtained fortuitously during the smelting of copper. Iron had limited use as a scarce and precious metal until about 3400 years ago when people in the Middle East and southeast Europe, discovered that wrought iron could be produced by heating a mass of iron ore and charcoal in a furnace. The process was later improved by having a forced draft. Techniques for hardening iron were first developed by the Hittites of Anatolia (now Turkey) and they managed to keep these secret for nearly 200 years during their successful conquests of other peoples with inferior weapons. However, their defeat about 3200 years ago, allowed their iron making skills to be adopted widely and significant quantities of iron were soon being produced. The recognition of the superior qualities of hardened iron to bronze for use in implements and weapons led to iron largely replacing bronze in these uses, marking the transition from the Bronze Age to the Iron Age. The Iron Age commenced at later times elsewhere in the world, for example around 2600 years ago in China.

About 2000 years ago, ironworkers learned to make steel by heating wrought iron and charcoal in clay boxes for a period of several days. From about the 400s AD, ironworkers developed shaft furnaces with a short, shaft-like stack above the hearth, through which the hearth was charged with ore and charcoal. The Catalan forge, a type of shaft furnace developed in the 700s AD in northeastern Spain, forced air in at the bottom by water power. Blast furnaces, which are shaft furnaces that made molten iron, were developed in the mid 1300s and were used to produce pig iron that was further refined to make steel. These early furnaces required 10t of charcoal to make 1 t of metal, leading to the denudation of the forests of England during the 1500s. This use of charcoal later became unnecessary when in 1709, Abraham Darby, an ironmaster in Coalbrookdale, England, manufactured coke from coal by baking, and successfully used it to reduce iron ore. This was the beginning of the great industrial age that culminated in the steel age, made possible by the British inventor Sir Henry Bessemer who developed a process of refining molten iron with blasts of air in the Bessemer furnace or converter in 1855. In 1856, Charles and Friedrich Siemens, German-born brothers living in Great Britain, invented the open-hearth regenerative gas furnace process for making steel, and in 1878, William Siemens demonstrated that steel could be refined in an electric arc furnace.

Symbol	Fe
Atomic no.	26
Atomic wt	55.85
Specific gravity	7.87
Valence	2, 3, 4, 6
Melting point	1535°C
Boiling point	2750°C
Crustal abundance	4.6%
Preferred analysis method	inductively coupled plasma emission spectrometry
Routine detection limit	100 ppm

With the new steel making processes and major resources of iron and coal, Great Britain became the first of the modern industrial nations. In USA, the discovery of the Lake Superior iron-ore deposits in 1844, led to the development of major industrial centres in Pennsylvania and along the Great Lakes, and entry by USA into the industrial age.

In New Zealand, there were various attempts to smelt ironsands of the west coast of the North Island, beginning in 1849, but the high titanium content and fine grain size defeated traditional blast furnace technology. Following the second world war, new iron-steel making technology in the form of the direct reduction kiln and electric arc furnace was applied to the ironsands by the Department of Scientific and Industrial Research and others. This led to the setting up by the Government, in 1959, of the New Zealand Steel Investigating Company, with the objective of determining the technical and economic feasibility of manufacturing steel using ironsand. By 1964, following successful trials of the newly developed direct reduction technology, a process was chosen that produced sponge iron from ironsand concentrate with sub-bituminous Waikato coal as a reductant and Te Kuiti limestone as a flux. A steel mill was commissioned by New Zealand Steel Ltd at Glenbrook in 1970, to use ironsand from the Waikato North Head deposit to produce 150,000 t of steel per year. Further refinement of the process occurred throughout the 1980s and the construction of expanded production facilities took place in 1986. The current production capacity of the mill is 700,000 t of which 60% is exported. Mining operations were also established at Waipipi (1971) and Taharoa (1972) for export of titanomagnetite concentrate to Japanese steelmakers. Mines at Waikato North Head and Taharoa are still producing today, but the Waipipi mine closed in 1987.

The name iron comes from the old English *iren*, *isern* and *isen* (German Eisen) and the symbol Fe is from the Latin *ferrum*. Hematite is from the Greek *haimatites* meaning bloodlike, and magnetite is from the Latin *magneta* for the magnetic rock lodestone.

Major Ores and Minerals

Iron is the fourth most abundant element and second most abundant metal after aluminium in the Earth's crust. It is also abundant in meteorites, usually alloyed with nickel, being the principal constituent in iron meteorites (siderites) and a lesser constituent in iron-stone and stony meteorites. Naturally occurring native iron is rare and found in only a few localities, notably in basalts at Oviqak, Disko Island, western Greenland, and in carbonaceous sediments in Missouri, USA.

The main ore minerals of iron are hematite, magnetite, titanomagnetite, goethite (bog iron) and siderite (Table 1). Taconite is an iron-bearing flint-like, sedimentary rock containing varying amounts of hematite and magnetite in extremely fine form. Ilmenite is mined for titanium, although some byproduct iron may be produced.

Properties

Iron is one of the transition elements in Group VIII of the periodic table. It is a silvery white metallic element which is soft, malleable and ductile, and has a specific gravity of 7.87. In comparison to other important commercial metals, iron is a poor conductor of electricity. Iron is easily magnetised at ordinary temperatures but it is difficult to magnetise when heated, and at about 790°C, the magnetic property disappears on the conversion from alpha-iron to beta-iron.

Iron is a chemically active metal. It readily combines with carbon dioxide, oxygen, sulphur or silica to form carbonates, oxides, sulphides or silicates respectively. When exposed to moist air, iron corrodes to form rust, a reddish-brown, flaky, hydrated ferric oxide. Rusting is an electrochemical (galvanic) process in which the impurities present in iron form an

Name, Formula	Colour	Hardness	Density	Lustre	Crystal form	Transparency	Fracture
Chamosite (Fe,Mg,Al) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	greenish-grey, brownish or greenish-black	3	3.0-3.4	vitreous or earthy	monoclinic	opaque	uneven
Goethite Fe ₂ O ₃ .H ₂ O	brownish-black, yellowish or reddish	5.0-5.5	4.0-4.4	adamantine	orthorhombic	opaque	fibrous, brittle
Hematite Fe ₂ O ₃	grey to black	5.5-6.5	4.9-5.3	metallic (earthy when amorphous)	hexagonal	opaque	subconchoidal or uneven
Iron, native Fe	grey	4-5	7.3-7.8	metallic	cubic	opaque	hackly
Magnetite Fe ₃ O ₄	black	6	5.2	metallic or submetallic	cubic	opaque	subconchoidal
Marcasite FeS ₂	bronze yellow	6.0-6.5	4.9	metallic	orthorhombic	opaque	uneven, brittle
Melanterite FeSO ₄ .7H ₂ O	green to white, yellowish to yellowish-brown	2	1.9	vitreous	monoclinic	subtransparent to translucent	conchoidal, brittle
Pyrite FeS ₂	bronze to pale brass yellow	6.0-6.5	4.8-5.1	metallic	cubic	opaque	conchoidal, uneven
Pyrrhotite FeS	reddish or brownish, bronze or copper colour	3.5-4.5	4.4-4.65	metallic	hexagonal	opaque	uneven or imperfectly conchoidal, brittle
Siderite FeCO ₃	pale yellowish or buff-brownish & brownish-black to brownish-red	3.5-4.5	3.7-3.9	pearly or vitreous	hexagonal	opaque, rarely translucent	uneven, brittle
Titanomagnetite (Magnetite-ulvöspinel mixture) Fe ₃ O ₄ + Fe ₂ TiO ₄	black	6	4.8-5.2	metallic or submetallic	cubic	opaque	
Vivianite Fe ₃ P ₂ O ₈ .8H ₂ O	white, deep blue or green	1.5-2	2.7	pearly to vitreous	monoclinic	transparent to translucent	sectile

Table 1: Properties of some iron minerals.

electrical couple with the iron metal. A small current is set up, with water from the atmosphere providing an electrolytic solution.

Formation

Iron ores occur in a wide range of geological environments in deposits that formed over a period exceeding 3 billion years, although most current production is from Precambrian banded iron formations.

Banded iron-formations

Banded iron formations (BIF) are by far the main source of iron ore and contain more than 95% of the world's iron resources. BIF is a thin bedded or laminated sedimentary rock, of possible chemical or biochemical origin, that contains 15% or more iron and typically consist of iron-rich layers alternating with chert or quartz-rich layers. The dominant mineralogy of the iron-rich layers is used to classify the BIF into different facies: oxide (hematite and magnetite), carbonate (siderite), silicate (greenalite, chamosite and glauconite), and sulphide (pyrite). BIF deposits range from a few metres to 150 m thick and may extend laterally from a few kilometres to hundreds of kilometres. Most are early to middle Precambrian in age. Two main subtypes are recognised — Lake Superior and Algoma.

Lake Superior BIF occur intercalated with other sediments formed in a continental shelf environment, including quartzite, black carbonaceous shale, red shale, conglomerate, dolomite, massive chert, chert breccia and argillite. The BIF are considered to be chemically or biochemically precipitated, however there is disagreement over whether the iron is derived by erosion from nearby landmasses, from volcanic exhalations or by leaching from euxinic sediments. Common varieties are banded hematite (Hamersley in Western Australia), itabirite (Minas Gerais area in Brazil, Liberia and Venezuela), taconite (Mesabi Range in Minnesota, the Kursk region in Russia and Norway), jaspillite (Marquette Range, Michigan) and siderite (Michipicoten District in Ontario, Canada).

Algoma BIF are found mostly in Precambrian greenstone belts and are characterised by their association with predominantly volcanogenic sediments of a greywacke-volcanic association. The iron and silica are believed to be derived from volcanic effusive and hydrothermal sources along volcanic belts and deep fault or rift systems. Their formation and distribution were controlled by tectonic rather than by biogenic or atmospheric factors. Examples include Helen Mine at Wawa, Sherman Mine at Temagami, Griffith Mine at Ear Falls and Lake St Joseph, all in Ontario, Canada; Woodstock in New Brunswick, Canada; and Kudrem UK in India.

Many BIF deposits have been enriched by secondary processes such as weathering or hydrothermal activity.

Ironstone

Ironstones, also known as Minette ores or Clinton ores, are sedimentary deposits that typically contain lenticular, massive iron-rich beds, 30 cm to 10 m thick, interbedded

with shale and sandstone. The ore consists of oolitic or pelletal grains of goethite, hematite or chamosite in a matrix of iron oxide, chamosite, siderite, calcite or dolomite, commonly with variable amounts of clastic quartz. They are considered to have formed in shallow shelf (neritic) marine and estuarine environments, and range in age from late Precambrian to Tertiary. Deposits range up to billions of tonnes at grades between 30 and 55% Fe, averaging 30–35% Fe. Their low grade and relatively high phosphorous content has resulted in a worldwide decline in use, although they remain the principal source of iron in north-central Europe. Examples include the Clinton ores from New York to Alabama; Wabana in Newfoundland; and Minette ores of England, France, Luxembourg and Germany.

Bog iron

Bog iron ores consist of goethite, typically with oolitic or pisolitic textures, formed by biochemical breakdown of humic iron and ferrous bicarbonate in lake and swamp waters. They are presently forming in tundra areas of Canada and Scandinavia, temperate coastal areas of the eastern USA and Canada, and in volcanic provinces such as Japan and the Kurile Islands. Examples of ore deposits occur in Carboniferous and Permian sedimentary sequences in northern England and eastern USA. The deposits are low grade, typically contain about 28% Fe, and have relatively high concentrations of manganese, phosphorus, water and clay.

Ironsands (black sands)

Accumulations of magnetite and ilmenite in beach sands are common. Many such deposits have been studied as potential sources of iron ore, but few are of commercial value. Titanomagnetite ironsand beach and dune deposits on the west coast of the North Island, New Zealand, are some of the largest deposits of this type in the world. Similar magnetite-bearing coastal sand deposits in Japan, the Philippines and Indonesia have been mined for iron ore to a limited extent.

Igneous deposits

Igneous-related magnetite deposits occur as magmatic segregations in intrusive bodies or extrusive volcanic deposits. They typically have a mineral assemblage of magnetite, hematite and apatite. The apatite imparts high concentrations of phosphorus in the ore, generally 1–3% but up to 15%. Examples of the intrusive type include the Kiruna region in northern Sweden, Pea Ridge and Iron Mountain in Missouri, and Larap in the Philippines. These deposits are hosted by rhyolite, quartz porphyry or syenite porphyry. The Kiruna orebody crops out over a strike length of 4 km, extends down dip for at least 1 km and is 80–90 m thick. The ore contains 57–71% Fe, 0.03–1.8% P, >2% S and 0.7% Mn. The annual ore production of about 18 Mt, makes it the world's largest underground mine. Examples of the volcanic hosted deposits include El Laco in Chile, Cerro de Mercado in Durango, Mexico, and Iron Mountain in Missouri. They occur as iron-rich lava flows and tuffs interlayered with andesite or latite.

In addition to the deposits described above, large resources of titanium- and vanadium-rich magnetite occur as segregations in anorthositic, gabbroic and noritic sequences in layered complexes and plutonic intrusives, mostly of Precambrian age. The magnetite is accompanied by ilmenite and traces of pyrite, chalcopyrite, maghemite and pyrrhotite. The relatively high titanium content limits their potential as iron ore. Examples include the Bushveld Complex in South Africa, Egersund in Norway, Allard Lake in Quebec, Tahawus in New York and Duluth gabbro in Minnesota.

Contact metasomatic deposits

Contact metasomatic iron deposits, also known as pyrometasomatic deposits, are hydrothermal magnetite deposits formed by replacement of country rock near the contact with intrusive igneous stocks, dikes or sills. Magnetite is accompanied by hematite, carbonates, pyrite, chalcopyrite and pyrrhotite. The deposits vary in shape from tabular bodies to irregular to vein-like. Some of the most important examples of this class are skarn deposits, developed where the intruded rock is limestone, and characterised by calc-silicate minerals such as garnet, pyroxene and amphibole. They range in size between 5 and 200 Mt and typically grade 40% Fe. There are two main subtypes, calcic and magnesian. Calcic iron skarns are associated with intrusives of gabbro to syenite composition, whereas magnesian iron skarns are associated with granodiorite to granite intrusives. Examples of calcic iron skarns include Cornwall in Pennsylvania, Sarbai in Kazakhstan (725 Mt at 46% Fe) and Marmoraton in Ontario. The largest magnesian iron skarn deposit is Sherogesh in the Commonwealth of Independent States (234 Mt at 35% Fe). An example of pyrometasomatic replacement of non-carbonate rocks is El Romeral in Chile, where a diorite stock intrudes andesite porphyry and metasediments.

Residual iron laterite deposits

Iron may be selectively concentrated in residual deposits as weathering removes the more soluble silica and other materials. Weathering of ultramafic rocks such as serpentinised peridotites, pyroxenite and dunites under tropical conditions, may form laterite iron deposits with 40–55% Fe. Iron laterites form extensive mantles and plateaux, up to 20 m thick, but more typically less than 6 m thick, and consist of nodular red, yellow or brown hematite and goethite. Their high contents of water (up to 30%), alumina (up to 20%), chromium, nickel and cobalt, reduces their suitability as iron ore. Examples include Conakry in Guinea and deposits in Guyana, Indonesia, Cuba and the Philippines.

Uses

Iron is the dominant metal used in all modern societies. It is employed in construction, land and sea transport, household utilities, machinery and tools. By far the greatest amount of iron is used in processed forms, such as wrought iron, cast iron and steel (see below). Commercially pure iron is used for the production of galvanized sheet metal and electromagnets. Small amounts of iron compounds occur in natural waters, in plants and as a constituent of blood. Iron compounds are employed for medicinal purposes in the treatment of anaemia, when the amount of haemoglobin or the number of red

blood corpuscles in the blood is low. Iron is also used in tonics.

Processed forms

Pig iron is produced in a blast furnace and contains about 93% Fe, 3–4% C, 2–3% Si, 0.5–2% Mn and about 0.04% of both S and P. The term pig iron comes from an early method of pouring liquid iron from a blast furnace into moulds set around a central channel, like a group of piglets around their mother. However, today rather than being cast into pigs, most pig iron is used in making steel, with lesser quantities made into cast iron or wrought iron. Cast iron is an iron-carbon alloy with 2–4% C and 1–3% Si, that is extremely brittle when cast. Its hardness, low cost and ability to absorb shocks make it an important construction material. Wrought iron is commercially pure iron and contains about 0.08% C with a fine distribution of intermixed iron silicate (slag) making it malleable and enhancing corrosion resistance. Ingot iron contains less than 0.06% impurities, but its high production cost limits its use to applications specifically requiring its properties of extreme ductility, corrosion resistance, magnetic permeability or electrical conductivity.

Steel, an iron-carbon alloy, contains from 0.04% to 2.25% C, along with other impurities, such as S, P, Si and Mn, and controlled amounts of other metals that are added as alloying agents. Steel is ductile and malleable when cast. There are five main types of steels: carbon, alloy, high-strength low-alloy (HSLA), stainless and tool. More than 90% of all steels are carbon steels, which contain varying amounts of carbon and not more than 1.65% Mn, 0.60% Si and 0.60% Cu. Alloy steels have a specified composition, containing certain percentages of V, Mo, or other elements, as well as larger amounts of Mn, Si and Cu than regular carbon steels. HSLA steels cost less than the regular alloy steels because they contain only small amounts of the expensive alloying elements, but they are processed to have greater strength than carbon steels of the same weight. Stainless steels contain Cr, Ni and other alloying elements that keep them bright and rust resistant in spite of moisture or the action of corrosive acids and gases. Tool steels contain W, Mo and other alloying elements that give them extra strength, hardness and resistance to wear, especially at high temperatures.

A special group of iron alloys, known as ferroalloys, contain 20–80% of an alloying element such as Mn, Si or Cr, and are used in the manufacture of iron and steel alloys.

Price

Prices cover a wide range depending on the grade and the nature of the product, and most are fixed annually under long-term sales contracts. Two reference prices tend to dominate the international market: the delivered prices of Brazilian ore to northwest Europe and of Australian ore to Japan. In 1995, prices for Brazilian ore to Europe were US\$26.95 per tonne for Companhia Vale do Rio Doce (CVRD) MBR sinter feed and US\$49.14 per tonne for CVRD pellets, whereas prices for Hamersley ore to Japan were US\$27.15 per long ton for Hamersley fines and US\$35.89 per long ton for Hamersley lump. All prices are on a freight on board basis.

World Production and Consumption

Total world production of iron ore in 1995 was 1,018 Mt, at an average grade of about 54%, mostly from China (250 Mt of mostly low grade ore), Brazil (178 Mt), Commonwealth of Independent States (140 Mt), Australia (135 Mt), India (60 Mt), USA (62 Mt), Canada (38 Mt), South Africa (33 Mt), Venezuela (23 Mt) and Sweden (21 Mt) (dos Santos-Duisenburg and Traeger, 1996). World usage of scrap in steel production amounts to some 340 Mt annually. World production of steel during 1995 was 748 Mt, including 730 Mt of carbon steel and 15.2 Mt of stainless steel (Mytton, 1996).

Brazil (134 Mt) and Australia (131 Mt) each account for about 30% of the world's total exports of iron ore, and together with seven other countries, each with exports of 10 Mt or more, provide 94%. Captive arrangements, where steel companies own and operate iron ore mines, are important particularly in the USA, Canada and Australia. The largest importers of iron ore are Japan (120 Mt), Germany (44 Mt), China (41 Mt), South Korea (35 Mt) and France (20 Mt) (dos Santos-Duisenburg and Traeger, 1996).

World reserves of iron ore are about 150,000 Mt containing about 65,000 Mt of iron (Crowson, 1996). Major reserves occur in Russia and Ukraine (23,500 Mt Fe), Australia (10,000 Mt Fe), Brazil (6,500 Mt Fe), Canada (4,600 Mt Fe), USA (3,800 Mt Fe), China (3,500 Mt Fe), India (3,300 Mt Fe), South Africa (2,599 Mt Fe), Sweden (1,600 Mt Fe) and Venezuela (1,100 Mt Fe). World resources are estimated to exceed 800,000 Mt of ore containing more than 230,000 Mt of iron.

Ore Processing, Smelting and Refining

Iron ores are mainly produced at open-pit mines, although significant quantities of ore are mined by underground methods in France, Luxembourg and Sweden. In most cases, the ore is shipped a long distance from the mine to the iron and steel mill. Commercial iron ores are generally either merchantable ores or concentrating-grade ores. Merchantable ores, also known as natural ores or direct shipping ores, are ores that require little processing before shipping to the steel works, typically only crushing and sizing, and also in some instances, washing and gravity separation. The sizing yields coarse (6.4 mm and 100 mm) material for shipping. Fine ore is commonly sintered or pelletised. The ore typically contains 55–68% Fe on a dry-analysis basis with low phosphorus and other impurity levels.

Concentrating-grade ores require considerable processing using gravity, magnetic, flotation or selective flocculation-flotation systems to yield a uniform, high-quality iron ore pellet or sinter. They include a wide range of iron ore types containing goethite, hematite or magnetite, that are processed using a variety of procedures.

The smelting of iron involves the reduction of the iron ore to pig iron, followed by the treatment of the pig iron to make cast iron, wrought iron and steel. In pig iron production, the ore is smelted with coke and limestone in a blast furnace. Air or oxygen is preheated to temperatures of 540–870°C and blown in at the bottom. It burns the coke to carbon monoxide, which reduces the iron oxide ore to metallic iron. The limestone provides additional carbon monoxide and also slags off the silica, alumina and other impurities. In 1995, 526 Mt of pig iron were produced and contributed to 67% of world crude steel production (dos Santos-Duisenburg and Traeger, 1996).

In the direct reduction method, iron is made from ore without melting or making pig iron. In one form of this process, iron ore and coke are mixed in a revolving kiln and heated to a temperature of about 950°C. The reducing gas, carbon monoxide, is given off from the heated coke just as in the blast furnace and reduces the oxides of the ore to form sponge iron of much higher purity than pig iron. In another process, the reducing gas is obtained separately from natural gas. The absence of a coke making stage means that there is less pollution than in the blast furnace process. Direct reduced iron production reached 30 Mt in 1995.

Steel is made by several processes. In the open-hearth methods, the hearth of the furnace is open directly to the flames that melt the charge. Temperatures between 1540 and 1650°C are maintained by regenerative preheating. At each end of the furnace there is a fuel burner and a chequer chamber (chamber with firebricks arranged in a chequered pattern). While the furnace is burning, the exhaust gases are drawn off through the chequer chamber at the other end, and give up most of their heat to the bricks. The furnace automatically switches burners about every 15 minutes, reversing the flow of gases, so that the incoming fuel and air pass through the heated chambers and are warmed by the bricks. The rectangular furnace is filled from one side and molten steel is tapped from the other. The charge consists of molten pig iron, some hematite and limestone; the excess carbon, silicon and other impurities are oxidised by the hematite and combine with the limestone to form slag; sulphur is vaporised and also unites with manganese to form MnS. Phosphorus is removed by reactions with calcium in the refractory brick lining.

In the basic oxygen process, low-sulphur, low-phosphorus pig iron is converted into steel in a tilting barrel-shaped furnace, through which oxygen is blown to slag off the impurities. Desired amounts of carbon and manganese are added and mixed by air blowers. For the various ferroalloys, appropriate amounts of alloy metals are added to yield the desired steel.

In the electric-furnace process, electricity is used for heating and scrap steel is the main starting material used. The refining conditions can be strictly regulated, making electric furnaces particularly valuable for producing stainless steels and other highly alloyed steels that must be made to exacting specifications. Electric arc furnaces produce about one third of world steel output.

Steel is marketed in a wide variety of sizes and shapes, such as sheets, strips, rods, pipes, railway rails, tees, channels and I-beams. These shapes are produced at steel mills by rolling or forming heated ingots to the required shape. The working of steel also improves the quality of the steel by refining its crystalline structure and making the metal tougher.

Iron and steel production in New Zealand

At BHP New Zealand Steel's Glenbrook steel mill (Fig. 1), ironsand from the Waikato North Head mine is blended with Huntly sub-bituminous coal in the ratio of about 1.8:1, preheated in multiple hearth furnaces to about 650°C, and then fed into sloping rotary kilns 65 m long and 4.6 m in diameter. The kilns operate at a temperature of 1100°C and, during the flow-through time of about 12 hours, reduce the iron oxide to form sponge iron containing 70% Fe. The sponge iron, known as reduced primary concentrate, is melted in an electric arc furnace to produce molten pig iron plus a vanadium-rich slag, which is separated as a valuable by-product. Steel is made using both the basic oxygen process and the electric arc furnace process. Molten pig iron is converted to steel in a KOBM oxygen steel making furnace, whereas an electric arc furnace is used for producing steel from scrap steel. The steel is continuously cast as slabs up to 1.55 m wide x 0.21 m thick x 10 m long and then later processed by hot and cold rolling into pipe, rectangular hollow section and flat products.

New Zealand Occurrence and Resources

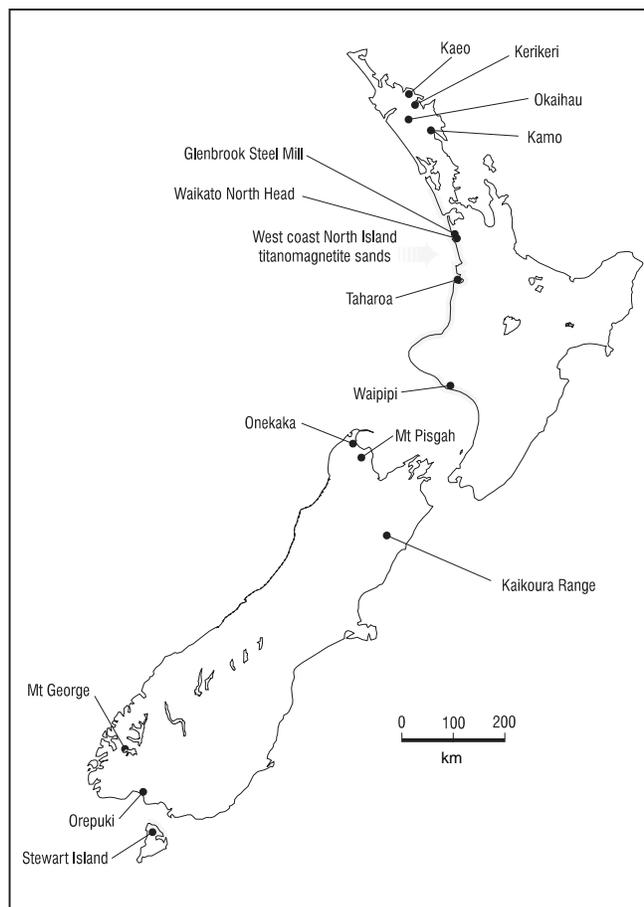
The occurrence of iron in New Zealand has been reviewed by Williams (1974), Officers of the New Zealand Geological Survey (1981) and Brathwaite and Pirajno (1993), and iron minerals found in New Zealand were listed by Railton and Watters (1990). The main type of iron ore deposits are titanomagnetite-rich coastal sands (ironsands), but there are minor deposits of bog iron in Northland, residual limonite deposits at Onekaka in Northwest Nelson, and magmatic segregations of magnetite-ilmenite in gabbro and anorthosite in Marlborough and Fiordland (Fig. 2).

Titanomagnetite ironsand placers, North Island

Titanomagnetite ironsand forms Quaternary onshore beach and dune deposits and offshore marine deposits along 480 km of coastline from Kaipara Harbour south to Wanganui on the west coast of the North Island (Fig. 3). The onshore deposits include the present beach and dune sand, and older coastal sand deposits that have been preserved by uplift due to faulting and/or lowering of sea level. The titanomagnetite was eroded from the Quaternary andesitic volcanic rocks of western Taranaki and the rhyolitic volcanic rocks of the Taupo Volcanic Zone, transported to the coast by rivers, along the coast by shallow-marine longshore currents, and subsequently concentrated by wave and wind action into beach and dune lag deposits (Ross, 1963; Kear, 1979; Hamill



Figure 1: Glenbrook steel mill, South Auckland makes local and export steel from ironsands mined at Waikato North Head (Photo: Lloyd Homer).



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Figure 2: Location of iron deposits in New Zealand.

and Ballance, 1985). Deposits present offshore on the continental shelf were probably concentrated under littoral conditions that existed on the continental shelf during the Holocene transgression (McDougall, 1961; McDougall and Brodie, 1967; Carter, 1980).

The onshore deposits were investigated in 1949 by Nicholson and Fyfe (1958), and later between 1957 and 1962 by the New Zealand Steel Investigating Co. Ltd (Kear, 1962, 1979). Nicholson and Fyfe (1958) conducted an aerial reconnaissance followed by sampling of selected areas. Rough estimates of the tonnage and grade of the deposits were calculated from contour plans and from samples taken from shallow holes (3–14 holes in each deposit) drilled with a 75 mm diameter post hole borer. The largest deposit identified was Waikato North Head, where the New Zealand Steel Investigating Co. Ltd carried out more detailed exploration including geological, ground magnetic and borehole surveys (Kear, 1979). An additional phase of exploration was conducted in the 1970s, and included magnetic surveys of the Waikato North Head and Taharoa deposits (Lawton, 1979).

Resource estimates of the ironsand deposits are given in Table 2. Deposits at Waikato North Head and Taharoa are currently mined, whereas a mine at Waipipi, near Waverley, closed in 1987.

The coastal sand deposits are subdivided into two geographic areas — a northern Auckland-Waikato region and a southern

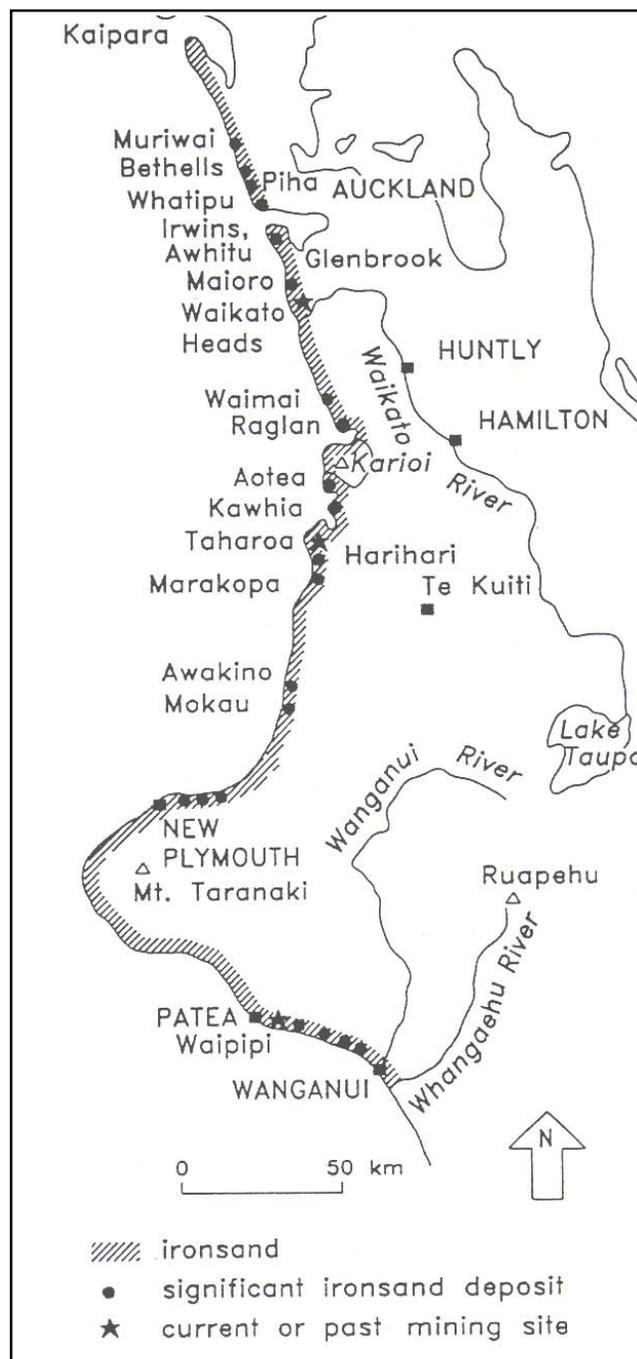


Figure 3: Location of titanomagnetite ironsand deposits, west coast, North Island.

Taranaki-Wanganui region. In the northern area, the Mitiwai, Bothwell, Hood and Awhitu sands or formations make up the Kaihu Group. The Mitiwai Sand (Holocene age) consists of present-day beach sand and sand bars along with drifting dune sand. The formation is up to 35 m thick and consists of loose, grey dune sand averaging about 20–25% titanomagnetite by weight, but up to 75% in the top half metre. Bothwell Sand (late Pleistocene to early Holocene) consists of up to 160 m of loose, grey dune sand, in some cases consolidated in the upper part, with 0–20% titanomagnetite, although some thin, richer layers contain up to 40%. The Hood Sand (mid Pleistocene) consists mainly of dune sand (Christie, 1979) and has a maximum thickness of

Deposit	Quantity of sand (Mt)	Grade (% magnetics)	Quantity of concentrate (Mt)
Muriwai*	90	15	13
Bethells*	20	15	3
Piha*	3.45	24	0.8
Whatipu*	17	31	5.3
Irwins*	30	18	5
Maioro North*	200	10	20
Maioro South†	150	21	30
Maioro South*	50	12	6
Waikato North Head†	780	18	140
Waimai*	98	44	43
Raglan†	78.7	19.7	15.5
Raglan*	49	20.4	10
Aotea*	500	?	?
Kawhia*	1500	13	200
Taharoa†	593	35	208
Harihari*	1	58	1
Marakopa*	55	45	25
Awakino*	9	63	5.8
Mokau*	10.5	37	3.9
New Plymouth*	33	24	8
Patea*	73.5	33	23.5
Waipipi†	153	26	40
Wanganui* Holocene	236	16	37
Rapanui	300	10	30

*Inferred estimate

†Indicated and/or measured estimate

Where both inferred and indicated figures are listed these are added together to give a total resource.

Table 2: Ironsand resources, west coast, North Island (after Brathwaite, 1990).

60 m, mostly of loose, grey sand, but it is weathered to clayey brown sand in the upper part. It typically contains up to 29% titanomagnetite but some parts, such as the Waiuku Blacksand Member, are very rich in titanomagnetite (30–60%) and are important in raising the grade of the deposits in the Waikato Heads, Waimai and Raglan areas. The Awhitu Sand (early Pleistocene) has a maximum thickness of 180 m, and consists of brown dune sand with clay, lignite and pumice. Titanomagnetite content is generally low but a few richer layers contain up to 16%.

In the Taranaki-Wanganui region, the late Quaternary coastal sands (Pouakai Group) are associated with a sequence of tectonically uplifted wave cut terraces that fringe the coast in a strip ranging from 1.6 km wide in north Taranaki to 16 km in Wanganui. In the south Taranaki-Wanganui coastal plain there are 12 separate terraces ranging in age from 700,000 to 60,000 years old (Pillans, 1983). The terraces consist of a basal wave cut platform overlain by a covered sequence of marine sand and gravel grading up into non-marine dune sands, peat, alluvial sediments, loess and volcanic deposits. The main ironsand deposits of economic interest are within the youngest of the terrace formations — Patea Dunesand or Rakaupiko Terrace. Weathered or ashy dune sand of potential

economic grade (>10% titanomagnetite) is present in some of the older terrace sequences, but high clay contents and occurrence under high quality farmland make these deposits less attractive for development.

The following descriptions of the ironsand deposits are drawn from a review of the ironsand resources of the west coast of the North Island by Brathwaite (1990) and Geological Resource Map reports for Manukau (Kermode *et al.*, 1992) and Te Kuiti (Christie *et al.*, 1992).

Muriwai: An extensive sandspit, some 50 km in length, extends northwards from Muriwai to Kaipara South Head (Schofield, 1973), however only the southernmost 3.2 km carries sufficient titanomagnetite to be of economic interest. Vegetated Holocene dunes cover an area of 1.8 km² and have an average thickness of 12 m. The resource estimate of Nicholson and Fyfe (1958) of 87.8 Mt of sand at 20% magnetics grade (17.6 Mt of concentrate), was based on 14 drill-holes, 4.5–9 m in depth, none of which reached sea level. A subsequent assessment by Kear (1962), using the Nicholson and Fyfe results together with drilling results from Kaiser Steel Ltd, determined an inferred resource of 90 Mt of sand at 15% magnetics grade (13 Mt of concentrate). This estimate was based on an average thickness of 12 m, which is the average height of the dunes above sea level.

Bethells (Te Henga): Vegetated and drifting Holocene dune sand fills a small coastal embayment and extends for up to 3 km inland along stream valleys. No drilling or sampling has been done. Very approximate resource estimates of 20 Mt grading 15% magnetics (3 Mt of concentrate) in Kear (1962), are based on conservative estimates of the area and thickness (9 m), and a grade extrapolated from other areas.

Piha: A 200–400 m wide strip of vegetated Holocene dune sand extends for about 2.3 km along a shallow coastal embayment. The resource estimate of 3.45 Mt of sand grading 24% magnetics (0.8 Mt of concentrate) (Nicholson and Fyfe, 1958), was based on 5 holes, 3–6.5 m in depth.

Whatipu: A low lying sand flat of mainly drifting Holocene sand extends northwards for 6 km from the north head of Manukau Harbour. The shoreline here is highly susceptible to change, and four phases of erosion and accretion over the past 150 years are recognised. The present 600 ha sand flat was built up only since the 1930s (Williams, 1977). The resource estimate of 17 Mt grading 31% magnetics (5.3 Mt of concentrate) by Nicholson and Fyfe (1958) was based on only 3 holes of 2.7–5 m in depth. Later work was carried out by Winstone Ltd (Carlson, 1972).

Hamiltons Gap and Irwins, Awhitu Peninsula: The Awhitu Peninsula extends for 40 km from Manukau South Head to the mouth of the Waikato River. It is an ancient sandspit, largely elevated to 150–180 m above sea level, and built up of Awhitu and Karioitahi formations, with Hood, Bothwell and Mitiwai formations mainly restricted to the southern part of the peninsula.

Awhitu Formation is generally low in magnetics and only two limited areas of economic grade are known — Hamiltons Gap and Irwins (4.7 km north of Hamiltons Gap). Apart from

2 drillholes, sampling is confined to road cuttings and coastal cliffs. Therefore there is potential for buried deposits, although they are likely to be clay rich, cemented to varying degrees, and covered by considerable thicknesses of barren overburden.

Maioro Area: The Maioro area extends for 16 km along the southern part of the Awhitu Peninsula and is bounded on the south by the Waikato North Head mine site area. A coastal strip of mainly Holocene vegetated dunes (0.5–1 km wide) overlies Bothwell and Karioitahi formations to the east.

In 1961, 46 holes were drilled on a reconnaissance 900 m grid pattern. Most holes were drilled to 12 m depth and four went down to about 30 m. Kear (1962) divided the area into two blocks for resource assessment. North of Karioitahi (Coast) Road, the drifting Holocene sand dunes were estimated to contain an inferred resource of 200 Mt at an average grade of 10%. The underlying older sand contained on average 4% magnetics. One hole, sited in the gap in the coastal hills through which the coast road passes, intersected an average of 14% magnetics over 27 m, below 12 m of Holocene sand.

The block south of Coast Road was estimated to contain an inferred resource of 150 Mt of Holocene dune sand at an average grade of 21%, with 50 Mt at 12% in the underlying Bothwell Formation. A subsequent round of fill-in, check and deeper drilling, carried out by New Zealand Steel (New

Zealand Steel, 1973), showed higher grades extending to slightly greater depths than the earlier drilling, so that a slightly larger resource is indicated.

Waikato North Head (BHP NZ Steel Ltd mine site, Fig. 4): Ironsand deposits on the northern side of the Waikato River are up to 120 m thick, with local very high grades (up to 75% magnetics). They comprise sands of the Waiuku Blacksand Member (Hood Formation), and the younger Mitiwai Sand, localised within a fault angle depression on the north side of the east-northeast striking Waikato Fault (Waterhouse and MacArthur, 1989). The ironsand deposit is predominantly composed of dune sand, with minor interbedded beach sand, tephra and mud (Christie, 1979).

Based on a 100 m grid drilling pattern, in situ resources have been estimated at 780 Mt of raw sand at an 18% magnetics grade (140 Mt of concentrate) (Waterhouse and MacArthur, 1989). Airborne magnetic surveys (Lawton, 1979) indicated that additional resources extend below sea level offshore to the west, and southwards under the Waikato River.

Mining of the deposit began in 1969, and production to the end of 1996 totalled about 12.75 Mt of concentrate. Current mining produces 1.4 Mt of concentrate per year using two large 1000 tph bucket wheel excavators linked to the concentrating mill by two moveable bench conveyors and a central trunk conveyor (see cover). In the concentrating mill, titanomagnetite grains are separated from non-magnetic



Figure 4: Waikato North Head mine which supplies ironsand concentrates to the Glenbrook steel mill (Photo: BHP New Zealand Steel Ltd).

minerals and clay in a wet magnetic separator followed by final upgrading by gravity separation using cones and spirals. The concentrate is pumped as a slurry 18 km to the Glenbrook mill.

Port Waikato: An active sandspit and overlying sand dunes cover an area of about 7.5 km², with an average height of about 4.5 m amsl with some parts over 30 m amsl. Kear (1979) noted that a single sample contained 22% magnetics, but he considered this to represent a maximum for the deposit. He tentatively estimated total resources to be more than 30 Mt at less than 22% magnetics.

Waikorea and Waimai streams area: Kaihu Group sands occur along a low lying stretch of coast in the Waikorea and Waimai streams area, bounded to the north, east and south by Tertiary rock with thin dune cover. Scout drilling by New Zealand Steel indicated that the southern part of the area was the most prospective, particularly south of Waimai Stream, because of preservation of a considerable thickness of the titanomagnetite-rich Waiuku Blacksand Member of the Hood Formation (Waterhouse, 1973). Inferred resources of ironsand in three of four blocks total 20 Mt of concentrate (42 Mt of sand at 47% magnetics); the northern (fourth) area was not included because of low grade (Waterhouse, 1973). The average grade for the Waimai area of 44% magnetics is considerably above average mine grades at Waikato North Head (18%) and Taharoa (35%).

Raglan North Head: At the north head of Raglan Harbour, coastal sands of the Kaihu Group have accumulated in an embayment on the northern side of a large headland formed by the Mt Karioi basalt-andesite volcano of Early Pleistocene age. The Raglan deposit was investigated with three shallow drill holes in 1949 (Nicholson and Fyfe, 1958), and was later drilled (11 drillholes) to an average depth of 22 m on a reconnaissance 600 m grid pattern in 1960–61 for New Zealand Steel (Kear, 1962; Waterhouse and White, 1994). In 1972, a further 10 holes were drilled to close up the grid to 300 m centres and to deepen some of the earlier holes to about 30 m depth. As shown by the drilling, Bothwell and Mitiwai formations overlie enriched Hood Formation with titanomagnetite-poor Awhitu Formation marking an economic base of the deposit. The average titanomagnetite contents of the sand units were determined as: Awhitu (2.5%), Hood (45%), Bothwell (12%) and Mitiwai (16%). The Mitiwai Formation increases in titanomagnetite concentration (up to 24%) inland. A resource of 25.5 Mt of concentrate has been estimated from drilling and is made up of 15.5 Mt indicated (78.7 Mt containing 19.7% magnetics) and 10 Mt inferred (49 Mt at 20.4% magnetics).

Aotea North Head and Kawhia: Large deposits of Kaihu Group sands occupy part of a coastal depression between the headland formed by the Mt Karioi volcano and greywacke basement rocks at Albatross Point 18 km to the south. The shallow, but extensive Aotea and Kawhia harbours are also contained within the depression. Older ironsand-poor formations (Awhitu Formation) crop out to the north of Aotea Harbour, and large dune fields of Holocene (Mitiwai)

sand are found at the north head of Aotea Harbour and between Aotea and Kawhia harbours.

Nicholson and Fyfe (1958) estimated a resource of 500 Mt of sand above sea level with an average grade of 5% magnetics (equating to 25 Mt of concentrate) in the dune sand deposit at the north head of Aotea Harbour. However, the grade estimate is based on only three shallow holes and appears low in comparison with an average grade of 9% magnetics at the nearby Kawhia deposit.

The Kawhia deposit is a large dunefield of mainly Mitiwai Formation covering an area of about 8 km long by 3 km wide. On the eastern side, the Mitiwai Formation overlies Bothwell Formation (or its equivalent) and older sand formations (Awhitu Formation and equivalents) of the Kaihu Group which are composed of silt, peat, mud and dune sand (Pain, 1976). Resource estimates by Nicholson and Fyfe (1958) and Kear (1962) are based on only 10 shallow (3 m) drillholes. Nicholson and Fyfe estimated the resource of raw sand as 2000 Mt at a grade of 9% magnetics (184.5 Mt of concentrate), but Kear rather arbitrarily reduced the tonnage to 500 Mt of sand at 10% magnetics (50 Mt of concentrate).

Taharoa (BHP New Zealand Steel Ltd mine site, Fig. 5):

The extensive dunefield at Taharoa is the largest of the ironsand deposits. It occupies a coastal depression, some 8 km in length and extending inland for about 2 km. The depression was formed by down-faulting of the basement greywacke to depths of up to 120 m below sea level, as determined by seismic refraction (Lawton, 1979), along east-west striking faults. The greywacke is directly overlain by Pleistocene–Holocene sand formations of the Kaihu Group (Stokes *et al.*, 1989). The currently worked deposits at Taharoa are loose grey aeolian sands of the Mitiwai Formation with titanomagnetite contents averaging about 40%, but up to a maximum of about 70%. These are underlain by less titanomagnetite-rich aeolian and beach sands of older formations of the Kaihu Group.

Reconnaissance drilling by Nicholson and Fyfe (1958) and Kaiser Steel Ltd (in Kear, 1962), and more detailed drilling by New Zealand Steel in 1969, resulted in an indicated resource figure for the Mitiwai Formation of 593 Mt grading 35% magnetics (208 Mt of concentrate). The subsurface geometry of the ironsand deposit was investigated using geophysical techniques (magnetics, gravity, seismic refraction and electrical methods) by Lawton (1979). From modelling of aeromagnetic anomaly patterns he inferred a total resource of 2560 Mt (565 Mt of concentrate), some of which is below sea level (200 Mt of concentrate). However, subsequent drilling has shown that the bulk of the deeper sands included in his estimates are of sub-economic grade (Stokes *et al.*, 1989).

Titanomagnetite concentrate has been mined from the site since 1972. An electric cutter suction dredge and floating concentrator extract and process sand, annually producing about 1.4 Mt of titanomagnetite concentrate (Fig. 5). The concentrate is pumped as slurry through a pipe to an offshore loading buoy and into an ore carrying ship. Total exports to

the end of 1996 were 31 Mt, mainly to Japan, with small quantities to South Korea and China.

Harihari area: A high level weathered remnant of Awhitu Formation caps a hill of Mesozoic greywacke about 1 km inland from the coast. The deposit lies at an elevation of about 150 m. Henderson and Grange (1922, p. 183) noted that “the deposit is horizontally bedded, and is evidently part of an ancient beach”. They described it as being about 30 m thick, covering an area of 1.2–1.6 ha, and containing about 1 Mt of “iron-ore”.

Marakopa area: A small area of moving and fixed (Mitiwai Formation) dunes, up to 50 m above sea level in height, occupies a coastal embayment at the mouth of the Marakopa River. The Mitiwai Formation overlies greywacke basement. The larger part of the deposit lies on the northern side of the river, where three holes averaging 4 m deep were drilled by Nicholson and Fyfe (1958). The average grade calculated from these holes is 53% magnetics, but this is biased by the distribution of the drillholes. An overall grade of the order of 45% magnetics is probably more reasonable. The inferred resource estimated by Nicholson and Fyfe was 55 Mt of raw sand, giving 29 Mt of concentrate at 53% grade or 25 Mt of concentrate at 45% grade.

Awakino and Mokau: The coastline south of Tirua Point is mainly formed by cliffs of Tertiary sediments, except

where the major rivers have cut wide river valleys. At the mouths of these rivers lie beach, sandspit, dune and alluvial sand deposits. Deposits of Mitiwai Formation at the mouths of the Awakino and Mokau rivers were investigated by the 1949 Nicholson and Fyfe (1958) survey. At Awakino, two holes drilled in the sandspit on the north side of the river mouth, showed grades of 63–65% magnetics over a depth of 2.4–10 m. Nicholson and Fyfe estimated an inferred resource of 9 Mt of sand at an average grade of 63% magnetics (5.8 Mt of concentrate). The three holes drilled in the Mokau deposit showed an average grade of 37% magnetics but only partly tested the full thickness of the sand above sea level. An inferred resource of 10.5 Mt of sand at 37% magnetics (3.9 Mt of concentrate) was estimated.

Older raised beach and dune deposits, equivalent to the Rapanui Formation of the Patea-Wanganui area, cap coastal terraces along 20 km of coastline from Awakino south to Tongaporutu. These older deposits have not been prospected, but, although they contain ironsand at the base, they are overlain by up to 24 m of andesite sand and laharic debris in the New Plymouth area to the south.

New Plymouth Area: Five small deposits of Holocene Patea Dunesand occur at intervals along 13 km of coastline from Waitara to Fitzroy. The deposits were investigated in the 1940s (Hutton, 1945; Beck, 1947), and in 1961 a



Figure 5: Taharoa ironsand mining operation has a dredge and concentration plant (foreground), dry mining plant, offices, workshops and stockpile (right centre). The Taharoa Maru, 2.5 km offshore, loads ironsand by an undersea pipeline (Photo: BHP New Zealand Steel Ltd).

reconnaissance drilling programme was carried out to check on the previous work (Kear, 1962).

The average thickness of the deposits is 3 m, with an average grade of 24% magnetics, decreasing with depth. The magnetic grains contain a high proportion of composite grains with inclusions of silicate minerals, which reduces the iron content of the concentrate to an average of 46% Fe compared with the overall average of 56% Fe for west coast ironsands. The high proportion of composite grains (middlings) is a reflection of proximity to the andesite source rocks of Mt Taranaki. A few of the drill holes penetrated older dune sand below the Patea Dunesand, but generally it is underlain by beds of clay, lignite and andesite debris.

The potential for discovery of significant additional quantities of economic grade ironsand, either along the coast from, or inland, from the known deposits is regarded as poor.

Patea Area: This is a coastal strip of Holocene Patea Dunesand, 1 to 4 km in width, extending 35 km southeast from Manutahi to Waitotara River. The area, which includes the Waipipi deposit, was drilled and assessed by the Mines Department in 1939 (see Mason, 1945; Kear, 1962). This work was subsequently reviewed and extended by further sampling in 1961 (Kear, 1962). The resource assessment was essentially confined to the Patea Dunesand which was shown by drilling to range in thickness from 2.4–7.3 m. The resource was estimated at 45.5 Mt of raw sand at 31.8% magnetics (14.5 Mt of concentrate) as drill-indicated, plus 28 Mt of sand at 32% (9 Mt of concentrate) as inferred in lateral extensions of the drill-indicated blocks.

The underlying older formation (Rapanui Sand) was reported as being low grade (8% magnetics) although little systematic testing appears to have been done. Kear (1962) noted that there was a volume of over 16 Mt of Rapanui Sand in the Waverley area (Waipipi) that would be worth

testing if an ironsand mining operation was developed in the area.

Waipipi: The Waipipi deposit lies within the Patea area described above and consists of Patea Dunesands overlying Rapanui Dunesand, with a lignite-clay unit defining the economic base of the deposit (Judkins, 1989). The Rapanui Dunesand is crossbedded and to some extent cemented by limonite and interstitial clay. The dune sands contain layers of peat, clay, volcanic ash, iron pan and organic material. The ironsand orebody extends over an area of 20 km² and averages 9.75 m in thickness.

The Waipipi deposit was mined between 1971 and 1987 using a floating dredge similar to that at Taharoa (Fig. 6). During this period, 15.7 Mt of concentrate at a grade of 56% iron and 7.8% TiO₂ was recovered from 60 Mt of sand, and exported to Japan where it was used for blending in blast furnace steel production. The project was started by Marcona Corporation which later became part of BHP-Utah International. When the operation closed, some 92 Mt of raw sand at 26% magnetics (24 Mt of concentrate) and 10 Mt of tailings at 24% magnetics (2.4 Mt of concentrate) were left unmined. The ore reserve estimation was based on drilling on sections 250 m apart, with later fill-in drilling at 125 m centres for mine planning and grade control.

Wanganui Area: This area extends for 27 km between the Wanganui and Waitotara rivers and includes the Westmere, Kai Iwi, Okehu and Nukumarū dune complexes. These dune complexes were investigated by Fleming (1946) and resource estimates of the Holocene dunesands were based on calculation of the volume of the dunes from elevation data and surface sampling. The resulting resource estimate, combined with that for the area between Nukumarū dune complex and the Waitotara River, gives a total tonnage of 236 Mt of sand at 16% magnetics (37 Mt concentrate) Kear (1962).



Figure 6: Ironsand dredge and floating concentrating plant at the former Waipipi mine, near Waverley (Photo: Bruce Thompson).

Assessments of the ironsand potential of the older sands (Rapanui and Brunswick) were given by Fleming (1953) and Kear (1962), the latter being based on a 1961 survey. For the Rapanui Sands a total inferred resource of 300 Mt at 10% magnetics (30 Mt of concentrate) was estimated by Kear, although the grade figure is based on only limited surface sampling and is conservative. The Rapanui Sands are overlain by 6 m of overburden. For the Brunswick Sands, Kear concluded that the average grade of 7% magnetics was uneconomic although the basal beach sand beds (3–6 m thick) are richer (18.5% magnetics from 4 samples).

Magnetite ironsand placers, South Island

Magnetite, along with ilmenite and locally zircon, is found in the heavy mineral fractions of Holocene beach placer deposits (black sands) along the coast of Fiordland, Southland and Stewart Island. Individual localities include Coal River (Hancock, 1972), Grace Burn (Watters, 1980), Te Wae Wae Bay (Nicholson, 1969), Orepuki and Riverton (Martin and Long, 1960; Nicholson, 1969; Wood, 1969) and Stewart Island (Williams and Mackie, 1959; Bell, 1971).

Miscellaneous iron-bearing sediments

Thin sideritic (iron carbonate) beds and concretions containing minor amounts of rhodochrosite (manganese carbonate) have been recorded in the Late Cretaceous Glenburn Formation west of Riversdale, eastern Wairarapa (Moore, 1980). Thin beds of siderite have been found in coal measures such as in the Greymouth area (Morgan, 1911) and in the Collingwood area of west Nelson (Ongley and Macpherson, 1923).

Hematite-bearing sands, with up to 24.4% iron, occur west of Herbert, 20 km south of Oamaru, at the Waianakarua River, and between Diamond Hill and Government Hill (Brown, 1938). The deposits probably represent weathered, Tertiary, glauconitic sandstones near the contact with the underlying schist basement.

Lenses of magnetite-bearing sandstone occur within some of the Jurassic sediments of the Murihiku Supergroup in the Wairepa Valley and on Dromedary Ridge in the Catlins area of southern Otago, and have been interpreted as representing fossil beach placer deposits (Willett, 1942; Speden, 1971).

Bog iron limonite deposits of Northland

Small limonitic bog iron deposits occur near Kaeo, Okaihau, Kerikeri and Kamo. They have been formed from leaching of ferrous iron from Kerikeri Basalt by carbonated surface and ground waters with subsequent deposition at the surface of ferric hydroxides.

The Potaetupuhi Bush deposit on the Okaihau-Kerikeri Road consists of small patches of high grade limonite (average analysis of 43.1% Fe) that extend over a total area of 4 ha (Bell and Clarke, 1909). Another deposit near Okaihau, has been intermittently worked, producing a combined total of 39,111 t up until 1961. The material was used as an agricultural stock lick to relieve “bush-sickness”, as an absorbent in the purification of coal gas, as a colouring agent in bricks, and as road metal. The deposit is less than 1 m thick and some

60,000 t containing 60% Fe₂O₃ remain. The deposit near Kamo has been intermittently worked, producing 26,165 t of ore up until 1961. The deposit near Kaeo contains between 10 and 36% Fe₂O₃ and may be an exhumed fossil laterite. Similar buried deposits could be discovered elsewhere in the region (Williams, 1974).

Redeposited lateritic limonite, Onekaka

Bodies of surficial limonitic iron ore occur in a belt from Ironstone Creek, Onekaka, north to the Parapara Inlet. They lie mainly on Arthur Marble and are preserved in a fault-angle depression (Bishop, 1971). The material is thought to be laterite, transported from the Tertiary peneplain and deposited in caves within the marble (Grindley and Watters, 1965). The material consists of hydrous iron oxides, and is compact, spongy, botryoidal, or earthy, with a mineralogy of limonite, goethite, turgite (hydrohematite), quartz and mica, and less commonly, pyrite and selenite (Williams, 1974).

Onekaka ore was first mined by Maori for use as a colouring medium (Williams, 1974). Small quantities were quarried in the 1880s and 1890s for use in paint manufacture. About 813,000 t were mined between 1922 and 1935 to produce 40,640 t of pig iron (Grindley and Watters, 1965). A small amount was also mined for use in gas purification. Landreth (1946) estimated total indicated and inferred resources of 9.65 Mt of ore at an average grade of 40% Fe, and gave individual average grade figures of 51.79% Fe (Washbourne), 45.17% Fe (Onekaka), and 50.48% Fe (Tukurua).

Magmatic deposits

Mt Pisgah, Northwest Nelson: At Mt Pisgah, minor magmatic segregations of magnetite and ilmenite occur in bands up to 0.5 m thick in metagabbro or metadiorite (Williams *et al.*, 1959).

Kaikoura Range, Marlborough: On Crows Nest, just north of Mt Tapuaenuku, leucogabbro and anorthosite contain layers of magnetite and ilmenite up to several metres in thickness. The high concentration of magnetite in the rocks (up to 50%) accounts for a very large magnetic anomaly (+500 gammas) on the 1:250 000 scale aeromagnetic map (Reilly, 1970; Hatherton, 1978).

Central Fiordland: Magnetite and ilmenite are found in stratiform bands within gabbroic to dioritic intrusions at Mt George and other locations in central Fiordland, described in the titanium mineral commodity report (Christie and Brathwaite, in prep.).

Past Production, Resources and Future Potential

Small quantities of iron ore were mined at Onekaka during the late 1800s, and about 813,000 t were mined between 1922 and 1935. Remaining resources are about 10 Mt at an average grade of 40% Fe.

The Waikato North Head and Taharoa mines had produced about 12.8 Mt and 31 Mt of concentrate respectively up to the end of 1996. The concentrate from Waikato North Head is the

raw material used to make steel at the Glenbrook Mill of BHP New Zealand Steel Limited. The steel products are for domestic consumption and for export, and include very high-purity stainless steels. The entire production from Taharoa, in addition to the 15.7 Mt of concentrate that was mined from 1971 to 1987 at Waipipi, has been exported to Japan, South Korea and China for blending in blast-furnace steel making.

The titanomagnetite ironsand deposits of the west coast, North Island, contain a total identified resource of over 850 Mt of concentrate assaying 55–56% Fe, 7–9% TiO₂ and 0.3–0.4% V₂O₅. Estimated in-ground ore resources at present operating mines are: Waikato North Head — 140 Mt of concentrate and Taharoa — 208 Mt of concentrate. A small resource remains at the Waipipi deposit. There are eight other medium to large deposits, each containing a resource of greater than 20 Mt of ironsand concentrate. Four of these are in the Waikato region: namely Waimai (>43 Mt of ironsand concentrate), Raglan (~20.5 Mt), Kawhia (~200 Mt) and Marakopa (>25 Mt). The Aotea deposit also contains a large volume of ironsand (500 Mt of sand), but insufficient drilling has been done to estimate the grade. Waimai is the best of these deposits in terms of grade, but Kawhia has the greatest size potential. For many of the deposits exploration drilling has been only on a reconnaissance scale and was carried out in the 1940s, 50s and early 60s, and therefore there is scope for improving the resource estimates with modern exploration.

Future Trends

The demand for iron will continue as industry and the population expand, and new applications are developed, such as the use of steel as a wood substitute in house frames. New Zealand's ironsand resources are sufficient for well into the future, however special steel shapes and steel alloys need to be imported. New Zealand titanomagnetite has proven amenable to the production of high purity steels, but it is different from most other iron ores, requiring specialised technology and market development. Production of added-value iron and steel products in New Zealand rather than export of the raw material ironsand should be the goal.

On world markets, demand and prices for iron ore and steel have improved and apart from minor fluctuations, are expected to increase because of growing markets in Asia, particularly China and South Korea. Internationally, blast furnaces are still a major method of steel production and steady developments have increased their efficiency and reduced their coke consumption. However, some equipment, particularly coke ovens, are near the end of their useful lives and in many instances replacement would not be economically viable. Also, environmental pressures and regulations will force closures of many coke ovens in the near future. This will require increasing use of the direct reduction process to manufacture the raw material for steel production, and increasing use of scrap iron and steel in the electric arc furnace production of steel.

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References

- Beck, A.C. 1947: Ironsand deposits at Waitara, New Plymouth. *New Zealand journal of science and technology B28*: 307–313.
- Bell, A.B. 1971: Conclusions on the reconnaissance survey of the sands of northeast Stewart Island: Frontier Contractors Ltd. Unpublished open-file mining company report, Ministry of Commerce M2129.
- Bell, J.M.; Clarke, E. de C. 1909: The geology of the Whangaroa subdivision. *New Zealand Geological Survey bulletin 8*.
- Bishop, D.G. 1971: Sheet S1, S3, and pt. S4 Farewell — Collingwood. Geological Map of New Zealand 1:63 360. Wellington. Department of Scientific and Industrial Research.
- Brathwaite, R.L. 1990: Ironsand resources of the west coast North Island. Unpublished contract report no. 1990/5 for Electricorp, DSIR Geology & Geophysics.
- Brathwaite, R.L.; Pirajno, F. 1993: Metallogenic map of New Zealand. *Institute of Geological and Nuclear Sciences monograph 3*.
- Brown, D.A. 1938: Moeraki subdivision. *New Zealand Geological survey annual report 32*: 9–12.
- Carlson, J.R. 1972: Preliminary report — Whatipu area: Winstone Ltd. Unpublished open-file mining company report, Ministry of Commerce M0288.
- Carter, L. 1980: Ironsand in continental shelf sediments off western New Zealand — a synopsis. *New Zealand journal of geology and geophysics 23*: 455–468.
- Christie, A.B. 1979: Sedimentary structures in Quaternary ironsands at Waikato North Head, New Zealand. *New Zealand journal of geology and geophysics 22*: 213–226.
- Christie, A.B.; Burrows, M.W.; Brathwaite, R.L.; Brown, L.J. 1992: Sheet QM301 Te Kuiti, Geological Resource Map of New Zealand 1:250,000. *Institute of Geological & Nuclear Sciences science report 92/16*.
- Christie, A.B.; Brathwaite, R.L. in prep.: Mineral commodity report 16 — Titanium. *New Zealand mining 23*.

- Crowson, P. 1996: Minerals handbook 1996–97. London, MacMillan Press. 455 p.
- dos Santos-Duisenberg, E.; Traeger, R. 1996: Iron ore. Pp. 50–52 *in*: Metals & minerals annual review, 1996. Mining Journal Ltd.
- Fleming, C.A. 1946: Magnetic ironsand-ores west of Wanganui. *New Zealand journal of science and technology B27*: 347–365.
- Fleming, C.A. 1953: The geology of the Wanganui Subdivision. *New Zealand Geological Survey bulletin 52*.
- Grindley, G.W.; Watters, W.A. 1965: Chapter 3: Geology. National Resources Survey, Part IV, Nelson Region. Wellington. Department of Scientific and Industrial Research, Government Printer.
- Hamill, P.F.; Ballance, P.F. 1985: Heavy mineral rich beach sands of the Waitakere coast, Auckland, New Zealand. *New Zealand journal of geology and geophysics 28*: 503–511.
- Hancock, P.M. 1972: Geological report on Coal River property, MPW549, Fiordland: Corona Ores and Minerals. Unpublished open-file mining company report, Ministry of Commerce M1781.
- Hatherton, T. 1978: Magnetic anomalies. *In*: Suggate, R.P.; Stevens, G.R.; Te Punga, M.T. eds, The geology of New Zealand. Wellington, Government Printer.
- Henderson, J.; Grange, L.I. 1922: Notes to accompany a geological sketch map of the marakopa district. *New Zealand journal of science and technology 5*: 177–183.
- Hutton, C.O. 1945: The ironsands of Fitzroy, New Plymouth. *New Zealand journal of science and technology B26*: 291–302.
- Judkins, D.C. 1989: The development of the Waipipi ironsands. *In*: Kear, D. (ed), The mineral deposits of New Zealand. *Australasian Institute of Mining and Metallurgy monograph 13*: 111–116.
- Kear, D. 1962: Geology of ironsand resources of New Zealand. New Zealand Steel Investigating Company Report (unpublished), 181 p.
- Kear, D. 1979: Geology of ironsand resources of New Zealand. Department of Scientific and Industrial Research, Wellington, 154 p.
- Kermode, L.O.; Meshesha, M.Y.; Christie, A.B.; Brathwaite, R.L.; Brown, L.J. 1992: Sheet QM281 Manukau, Geological Resource Map of New Zealand 1:250,000. *Institute of Geological & Nuclear Sciences science report 92/15*.
- Landreth, R.F. 1946: Iron ore reserves of the Onekaka field, NW Nelson: Mines Department. Unpublished open-file mining company report, Ministry of Commerce M0763.
- Lawton, D.C. 1979: Geophysical exploration of New Zealand ironsand deposits. Unpublished PhD Thesis, University of Auckland.
- Martin, W.R.B.; Long, A.M. 1960: Heavy mineral content and radioactivity counts of beach sands west of Oreti river mouth to Blue Cliffs, Southland, New Zealand. *New Zealand journal of geology and geophysics 3*: 400–409.
- Mason, B. 1945: The utilisation of New Zealand ironsands as a source of iron, titanium and vanadium. *New Zealand journal of science and technology B26*: 227–238.
- McDougall, J.C. 1961: Ironsand deposits from the west coast, North Island, New Zealand. *New Zealand journal of geology and geophysics 4*: 283–300.
- McDougall, J.C.; Brodie, J.W. 1967: Sediments of the western shelf, North Island, New Zealand. *New Zealand Oceanographic Institute memoir 40*, 56 p.
- Moore, P.R. 1980: Late Cretaceous-Tertiary stratigraphy, structure, and tectonic history of the area between Whareama and Ngahape, eastern Wairarapa, New Zealand. *New Zealand journal of geology and geophysics 23*: 167–177.
- Morgan, P.G. 1911: Geology of the Greymouth subdivision. *New Zealand Geological Survey bulletin 13*.
- Mytton, M. 1996: Steel. Pp 52–54 *in*: Metals & minerals annual review, 1996. Mining Journal Ltd.
- New Zealand Steel Limited 1973: Report on ironsand prospecting New Zealand Steel Ltd, 31 December 1972. Unpublished open-file report mining company report, Ministry of Commerce M0601.
- Nicholson, D.S. 1969: A reconnaissance survey of economic minerals in South Island east coast beach sands and some river gravels. *New Zealand journal of science 12*: 111–117.
- Nicholson, D.S.; Fyfe, H.E. 1958: Borehole survey of North Island ironsands from New Plymouth to Kaipara Harbour. *New Zealand journal of geology and geophysics 1*: 617–634.
- Officers of the New Zealand Geological Survey 1981: Minerals of New Zealand (Part A: metallics 2nd Ed.). *New Zealand Geological Survey report 38A*.
- Ongley, M.; MacPherson, E.O. 1923: The geology and mineral resources of the Collingwood subdivision. *New Zealand Geological Survey bulletin 25*.
- Pain, C.F. 1976: Late Quaternary dune sands and associated deposits near Aotea and Kawhia Harbours, North Island, New Zealand. *New Zealand journal of geology and geophysics 19*: 153–177.
- Pillans, B. 1983: Upper Quaternary marine terrace chronology and deformation, south Taranaki, New Zealand. *Geology 11*: 292–297.
-

- Railton, G.T.; Watters, W.A. 1990: Minerals of New Zealand. *New Zealand Geological Survey bulletin 104*.
- Reilly, W.I. 1970: Sheet 16 Kaikoura. Magnetic Map of New Zealand, 1:250 000, Total Force Anomalies. Wellington. Department of Scientific and Industrial Research.
- Ross, D.I. 1963: Surface magnetic permeability measurements of some Taranaki ironsand deposits. *New Zealand journal of geology and geophysics 6*: 197–208.
- Schofield, J.C. 1973: New Zealand Steel Ltd drilling — Muriwai Lease — ironsand reserves and geology. *New Zealand Geological Survey report M30*.
- Speden, I.G. 1971: Geology of Papatowai subdivision south-east Otago. *New Zealand Geological Survey bulletin 81*.
- Stokes, S.; Nelson, C.S.; Healy, T.R.; MacArthur, N.A. 1989: The Taharoa Ironsand Deposit. In: Kear, D. (ed), Mineral Deposits of New Zealand. *Australasian Institute of Mining and Metallurgy monograph 13*: 105–109.
- Waterhouse, B.C. 1973: N.Z. Steel Ltd Drilling Programme Waikorea-Waimai. Unpublished open-file company report, Ministry of Commerce M0601.
- Waterhouse, B.C.; MacArthur, N.A. 1989: Geology of Waikato North Head ironsand deposit. In: Kear, D. (ed), Mineral Deposits of New Zealand. *Australasian Institute of Mining and Metallurgy monograph 13*: 99–103.
- Waterhouse, B.C.; White, P.J. 1994: Geology of the Raglan-Kawhia area, Sheet R14CD, R15, and part R16. *Institute of Geological & Nuclear Sciences geological map 13*.
- Watters, W.A. 1980: Letter to D.G. Bishop dated 1/4/80, New Zealand Geological Survey. Institute of Geological and Nuclear Sciences file B46/338, Dunedin.
- Willett, R.W. 1942: The occurrence of iron-ore in the Catlins District, south Otago. *New Zealand journal of science and technology 23B*: 227–230.
- Williams, G.J. 1974: Economic geology of New Zealand. *Australasian Institute of Mining and Metallurgy monograph series 4*.
- Williams *et al.* 1959: Economic minerals at Canaan, north west Nelson. Proceedings of a mineral conference, School of Mines and Metallurgy, University of Otago vol. 6, paper 140.
- Williams, G.J.; Mackie, J.B. 1959: Economic minerals of Stewart Island. Proceedings of a mineral conference, School of Mines and Metallurgy, University of Otago vol. 6, paper 125.
- Williams, P.W. 1977: Progradation of Whatipu Beach 1944–1976, Auckland, New Zealand. *New Zealand geographer 33*: 84–89.
- Wood, B.L. 1969: Geology of the Tuatapere subdivision, western Southland. *New Zealand Geological Survey bulletin 79*.
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