

MINERAL, COAL AND PETROLEUM RESOURCES: PRODUCTION, EXPLORATION AND POTENTIAL

Anthony B. Christie¹, Richard G. Barker²

¹GNS Science, PO Box 30-368, Lower Hutt 5040, New Zealand

²Consulting Geologist, PO Box 54-094, The Marina, Bucklands Beach, Auckland 2144, New Zealand

ABSTRACT: New Zealand has been a significant producer of minerals and coal since early European settlement in the mid-19th century, and of hydrocarbons since 1970. Current production consists of oil, gold and silver, high quality (bituminous) coal, ironsand and specialised industrial minerals such as halloysite china clay for export, and a range of minerals and rocks for domestic use that are fundamental to New Zealand's economy and infrastructure. The latter include aggregate for road making and construction (concrete aggregate and cement), coal for use by industry and electricity generation, and limestone for agriculture, cement making, and industry. Small quantities of diatomite, dolomite, perlite, pumice, serpentinite, and zeolite are also produced mainly for domestic markets. Other commodities that have been produced in the past include antimony, chromium, copper, lead, manganese, mercury, phosphate, platinum, sulphur, tin, tungsten, and zinc.

New Zealand has well-documented potential for the discovery of a wide range of minerals and of petroleum, both onshore and offshore. Exploration is essential for converting this resource potential to wealth-creating assets. The resource-related industries are significant economic contributors, but New Zealand's resource potential remains to be realised.

Mineral resources are created by natural processes and are generally described as non-renewable, implying they are finite, but many minerals (metals in particular) have been produced for several thousand years. Supplies have been maintained through exploration and the discovery of new resources, research that has determined the origin of mineral deposits and identified new exploration concepts, technological advances that have greatly improved the efficiency of mining and processing methods and reduced the demand for many metals, and conservation practices including recycling and the retreatment of mine waste material that extend existing supplies. Throughout history the combined effects of research, exploration, innovation, substitution and conservation have maintained mineral raw material supplies.

Key words: aggregate, clay, coal, exploration, gas, gold, ironsand, limestone, minerals, petroleum, production, resources.

INTRODUCTION

Compared with most other countries with a similar land area and population, New Zealand is relatively well endowed with natural mineral resources (see Box 1) such as gold, coal, oil, gas, ironsand, limestone, clay, zeolite, sand and construction aggregate (Figure 1). On land, these commodities have considerable capacity for expanded production, whereas offshore within New Zealand's Exclusive Economic Zone there is immense potential for new discoveries and development of oil and gas, methane, gas hydrates, placer gold, ironsand, volcanogenic massive sulphides (copper, zinc, lead and gold) and ferromanganese deposits (Figures 2 and 3).

MINING HISTORY

The mining industry has been a major contributor to New Zealand's economic development since the arrival of European settlers in the 19th century. Coal was the main primary energy source until the mid-20th century. The 19th century gold rushes led to the settlement of much of the South Island with gold rapidly becoming New Zealand's main export earner by the late 19th century.

Exploration for New Zealand's mineral resources began with Māori discoveries of greenstone (pounamu), and other rocks and minerals suitable for making weapons, tools, art and ornaments (see Box 2). Mineral exploration intensified when European settlers arrived in numbers in the mid-19th century. By 1869, gold, silver, copper and iron ores had all been discovered and worked, numerous other metals had been located, all of the main coal fields had been discovered, and coal was being produced from the Bay of Islands to Southland (Hector 1869). Concern about the poor performance of the coal mining industry, which

BOX 1

What is a mineral?

Mineralogists define minerals to include only those naturally-occurring inorganic elements or compounds with an orderly chemical structure. Under this definition coal and petroleum, being of organic origin, are not minerals. The Crown Minerals Act, under which Crown-owned minerals are managed in New Zealand, defines minerals to include solid minerals such as gold, limestone, and building aggregate, as well as oil, coal, petroleum and gas, but excludes geothermal fluid and groundwater. In this chapter, the term "minerals" is applied to inorganic, solid, naturally occurring materials, and does not include coal and petroleum although they are described separately in the chapter. Rocks are an aggregate of one or more minerals.

Coal is classed according to "rank". The three main terms used to describe coal rank in New Zealand are lignite, sub-bituminous coal, and bituminous coal, reflecting increasing energy content, increasing carbon content and reducing moisture content.

Minerals can consist of single chemical elements such as the metals copper, gold, iron, platinum, silver and liquid mercury; and the non-metal solids of carbon (diamond and graphite) and sulphur. Most minerals consist of several chemical elements that form crystals. Examples include quartz (SiO₂) and more complex minerals such as nephrite "greenstone" Ca₂(MgFe)₅(OH)₂(Si₄O₁₁)₂.

Most metals are produced by processing minerals that contain several elements.

Mineral resources are natural resources like air, water, and soil, but differ from them in needing to be discovered and their production maintained by continuing exploration and innovation.

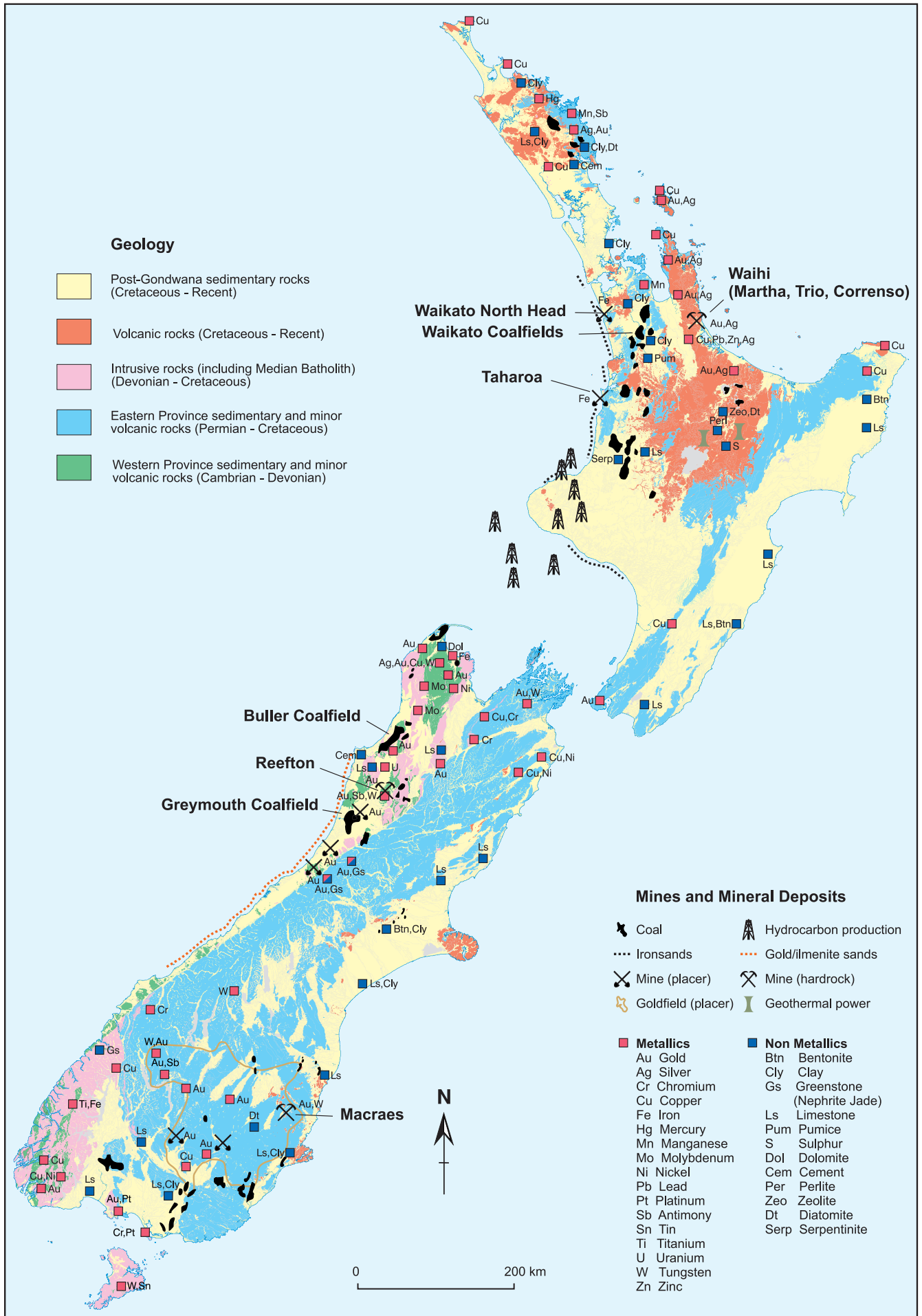


FIGURE 1 Geology, mines and mineral deposits.

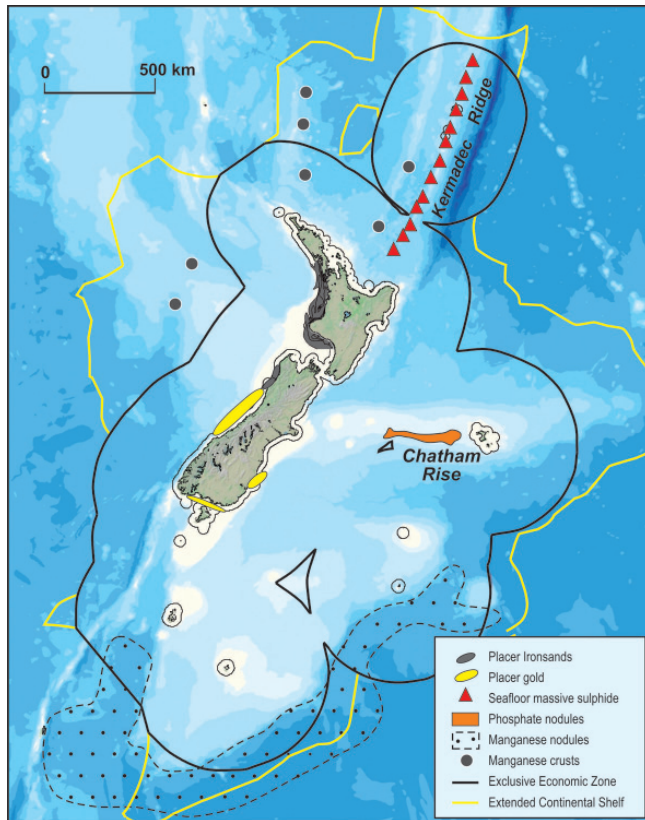


FIGURE 2 Offshore minerals.

was then the main energy source, led the government to acquire coal mining companies and become the predominant producer early in the 20th century.

Gold was the most valuable mineral produced in New Zealand during the 19th century, being overtaken by coal in the 1930s, and later by aggregate and non-metallic industrial minerals in the 1960s, when coal mine output declined (Williams 1974). Prolonged government-funded investigations into making steel from the very extensive titanomagnetite ironsand deposits of the west coast of the North Island were eventually successful, and a mill established at Glenbrook began producing steel from iron-sand in 1970.

Over the past 25 years the mining industry in New Zealand has grown strongly. A surge of investment in mineral exploration by the private sector, mainly by overseas companies in the 1980s, led to a number of new mineral discoveries, and new mines being developed. Coal output reached record levels in 2006, with growth being driven by coal exports for steelmaking (Figure 4). Gold output increased from less than 10 000 ounces (310 kg; see Box 3) in 1983 to more than 300 000 ounces (9330 kg) 10 years later (Figure 5). Gold output is being maintained by existing operations based on discoveries made in the 1980s.

The success of the mineral industry in New Zealand has depended on innovation and research. Major innovations include the 19th century development of the bucket ladder dredge for working placer gold in the South Island; application of the cyanide process of gold extraction that was first used commercially at Karangahake near Waihi in the 1880s; making steel from titanomagnetite ironsand after a century of investigation; applying the results of extensive research into active geothermal systems for electricity generation to the exploration of epithermal gold deposits in the 1980s; and undersea exploration for sea floor hydrothermal systems and massive sulphide deposits in the 2000s.

BOX 2

Ancient mineral use

Before European settlement, Māori prized greenstone (pounamu) for ornaments, tools and weapons, used argillite and obsidian for tools, and decorated their carvings and bodies with colours made from clays, limonite and vivianite. They were aware of coal (waro), but are not known to have used it for fuel.

New Zealand's mine production has been dominated by gold and coal since the 19th century. The total gross value of New Zealand's recorded gold production of 34 million ounces to date at current prices is close to NZ\$50 billion. About 280 million tonnes of coal has been produced to date with a current total value of at least NZ\$30 billion.

Oil was first produced in New Zealand in 1865 from Taranaki, but the first significant discoveries came a century later with two large gas-condensate fields: the onshore Kapuni field in the late 1950s and offshore Maui field in the late 1960s (Campbell et al. 2012). They supply natural gas for electricity generation, gas-to-gasoline, methanol, urea fertiliser, and industrial and home heating.

New Zealand's first significant commercial oil field, the McKee field, was discovered in 1979 in onshore Taranaki. Since 2000, four new fields have been developed in Taranaki – the onshore Pohokura and Kupe gas fields and the offshore Kupe and Maari oilfields (Figure 3). By the end of 2007 more than 10 oil and gas fields were producing, with two new fields to come on-stream, but the combined reserves of these new fields are still only about a quarter of the size of the declining Maui field.

CURRENT PRODUCTION

Statistics on New Zealand's mine production are maintained by New Zealand Petroleum & Minerals (NZP&M) and are published on their website (www.nzpam.govt.nz). The latest available statistics are for 2011 (Table 1, and Figures 6 and 7). Production is dominated by rock aggregates for use in roading and construction within New Zealand, coal for domestic use and exports, and gold that is largely exported. Ironsand, for local steelmaking and for export, and industrial minerals contribute to the total value that has been close to NZ\$2 billion per year in recent years.

CONTRIBUTION OF MINING TO THE NEW ZEALAND ECONOMY

New Zealand's mine production can be divided into two categories of about equal value:

- Exports, mainly of gold, high quality (bituminous) coal, iron-sand and specialised industrial minerals such as halloysite china clay.
- Materials produced for domestic use, mainly aggregate for road making, for construction (concrete aggregate and cement), coal for use by industry and electricity generation and industrial minerals used as raw materials by other industries and agriculture.

Export minerals are not constrained by the size of the domestic market, and for high value minerals such as gold, the location of a resource is not a significant factor in terms of operating transport costs. Geological potential is the primary determinant of the location of these mining operations. Exploration and development are

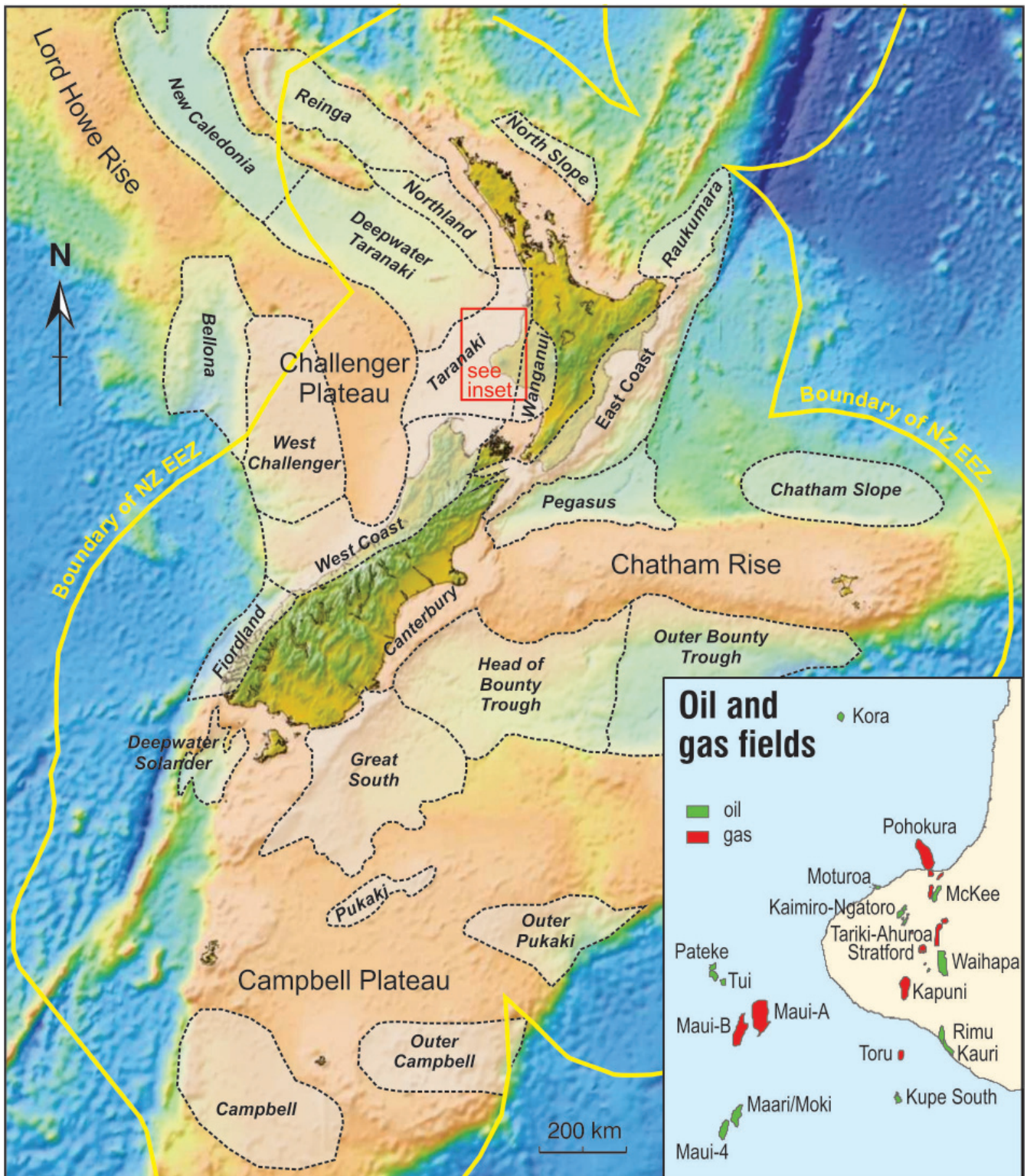


FIGURE 3 Offshore sedimentary basins with oil and gas potential. The inset map shows oil and gas fields of the Taranaki sedimentary basin.

largely influenced by the conditions under which access to the land can be obtained, and site-specific operational constraints.

Industrial minerals are also significant export commodities, and include ironsand, lime (Waikato), and the clay minerals halloysite (Northland) and bentonite (Canterbury). Other industrial minerals have been exported in smaller quantities.

Aggregate (see Box 4) and many of the industrial minerals (e.g. limestone for agriculture and cement making) are used to underpin domestic economic activity, where demand is determined by the size of the local market. If supplies of these materials are constrained, prices will rise, and more distant

sources may need to be used, increasing the cost and impact of transport. Total production of sand, rock, and gravel has averaged about 30 million tonnes per year over the last 10 years, equivalent to about 7 tonnes per person. On this basis, current total demand for aggregate in the Auckland metropolitan area is likely to exceed 7 million tonnes per year. An increasing proportion of the aggregate will be sourced from the south as quarries in the Auckland urban area close, due mainly to urban encroachment on areas with resource potential. The practical effect of this can be demonstrated by an example: if all the supplies of aggregate for Auckland were to be transported from the south by road in

BOX 3

Ounces

In the minerals industry, quantities of gold, silver, and platinum group metals are measured in troy ounces, where one troy ounce weighs 31.10 g. This is different from the imperial ounce, also known as the avoirdupois ounce, which weighs 28.35 g.

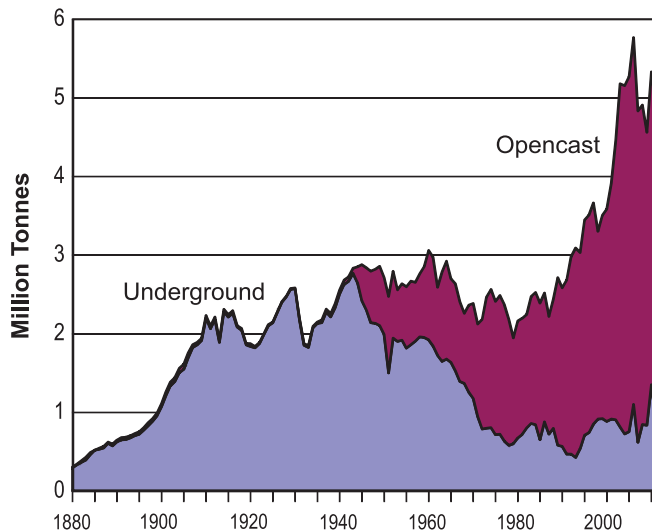


FIGURE 4 New Zealand coal production 1879–2011.

TABLE 1 New Zealand mineral production 2010 and 2011

| | 2010 | 2010 | 2011 | 2011 |
|---|----------------------|-------------------------|----------------------|-------------------------|
| | Quantity (tonnes) | Value (NZ\$ million) | Quantity (tonnes) | Value (NZ\$ million) |
| Metals | | | | |
| Gold | 13 494 | 664.0 | 11 7614 | 727.0 |
| Silver | 17 136 | 15.1 | 14 324 | 20.7 |
| Magnetite (Ironsand) | 2 438 641 | nr | 2 357 440 | nr |
| Total | 2 438 672 | 679.1 | 2 357 466 | 747.6 |
| Non Metals | | | | |
| Aggregate for building, roading, reclamation and fill, and decorative use | 26 652 630 | 283.3 | 25 831 518 | |
| Clay for brick, tiles etc. | 30 192 | 2.1 | 10 911 | |
| Clay for pottery and ceramics | 107 761 | 11.5 | 21 545 | |
| Dolomite for agriculture and industry | 385 347 | 18.8 | 141 502 | |
| Limestone and marl for cement | 448 294 | nr | 1 704 562 | |
| Limestone for agriculture | 1 686 024 | 30.9 | 1 373 207 | |
| Limestone for industry | 1 054 685 | 14.0 | 185 071 | |
| Other industrial minerals | 30 351 | 0.9 | 361 356 | |
| Pumice | 118 249 | 2.1 | 229 268 | |
| Silica Sand | 113 231 | 2.2 | 109 346 | |
| Total | 30 626 764 | 365.8 | 29 968 466 | 438.8 |
| Coal | 5 330 500 | nr | 4 944 800 | nr |
| GRAND TOTAL | 38 395 936 | 1045 | 37 270 732 | 1186 |

Note: 'Other industrial minerals' include amorphous silica, bentonite, diatomite, perlite, serpentine and zeolite. Value data exclude coal and ironsand. A detailed breakdown of production values for industrial minerals for 2011 is not available. 'nr' = not reported. Source: www.nzpam.govt.nz

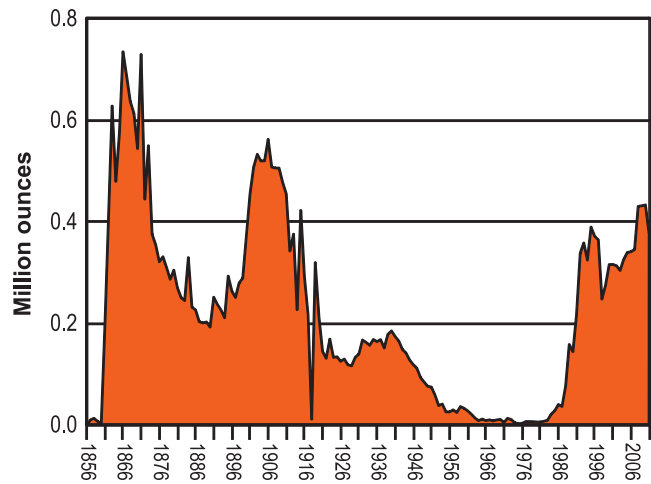


FIGURE 5 New Zealand gold production.

20-tonne truckloads, it would be equivalent to one round trip every 40 seconds along State Highway 1 during working hours. For these minerals, the location of mining operations in relation to their users has significant environmental and economic effects.

Road-making accounts for about 60% of the aggregate being produced in New Zealand, followed by building (aggregate for making concrete). Aggregate is needed also for preparing building sites (fill) and for coastal protection and reclamation.

Demand for aggregate and industrial minerals has been increasing in response to economic and population growth, particularly in the north of the North Island. Exports of some mineral commodities have also risen in recent years. For example, the value of coal production has been increasing rapidly until recently, due mainly to an increase in the volume and selling

price of export coal from the West Coast of the South Island. In contrast, gold output has been steady in recent years and iron and steel markets has fluctuated with world iron and steel markets.

Economic analysis (Walton et al. 2002) based on a geological analysis of New Zealand's mineral potential (Christie and Brathwaite 1999) has shown that New Zealand has the mineral potential to increase GDP by between 1.3% and 3.4%, with significant increases in household incomes (0.9% to 2.7%) and exports (2.3% to 8.6%). Since 1999, when the value of the resources was analysed for this study, commodity prices have dramatically increased, by up to six-fold in the case of copper, driven by rapidly increasing demand from developing countries (China and India particularly). Current prices would therefore imply much greater economic gains.

The economic contribution of minerals and petroleum has steadily increased in recent years (Figure 8). The contribution of mining to GDP has increased from about NZ\$500 million in 2001 to more than NZ\$1,500 million in 2009, the latest year for which this information is available. The contribution of petroleum increased sharply from 2007 when the Tui oilfield began producing. In 2010, New Zealand's most valuable export commodity was oil (after dairy production). The resource sector has been among New Zealand's fastest growing sectors since 2004. Numbers employed in the mining sector have doubled over the last decade (Figure 9).

Mining uses less than 0.05% of New Zealand's land area, and sites of former mines are now used for other purposes such as agriculture and tourism. Table 2 summarises recent estimates of the total area of land that is directly affected at present by a range of rural industrial land uses (including mining), and relates this to primary industry contribution to GDP for 2009.

The area affected by mining is small in comparison to its economic contribution. On a per-hectare basis mining is 25 times as productive as horticulture and viticulture, and more than 80 times as productive as dairy farming and milk processing. The contribution of petroleum to GDP for 2009 is included in Table 2 for comparison.

The area of land directly occupied by mining and related production activities is very small, and its effects are localised. The effects of mining activities on water quality are much easier to identify and control than are the effects of widely dispersed activities such as dairy farming, which directly affects an area of about 2 million hectares.

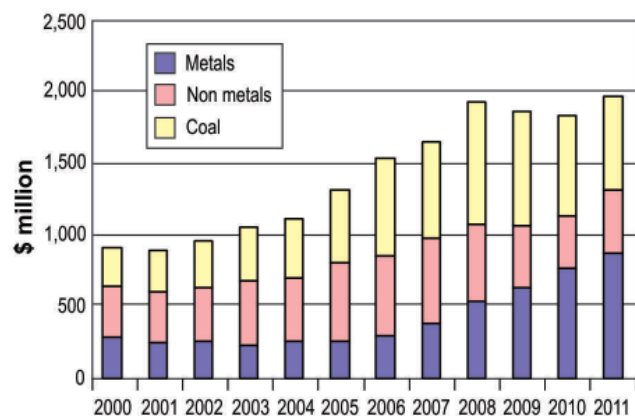


FIGURE 6 Value of New Zealand mine output 2000–2011. Source: NZ Petroleum & Minerals production data, industry price estimates.

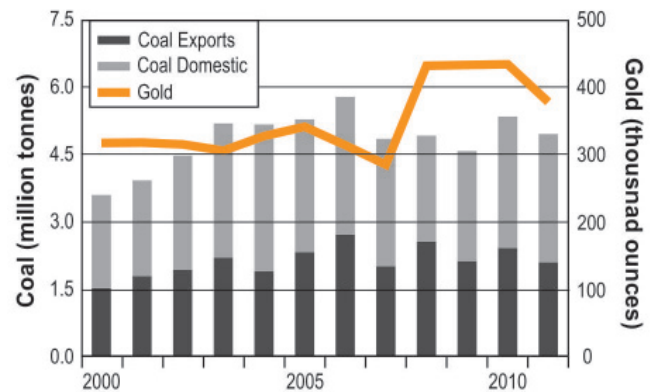


FIGURE 7 New Zealand gold and coal production 2000–2011. Source: NZ Petroleum & Minerals.

WHAT IS A RESOURCE?

Mineral resources

Mineral resources differ from other resources in two main ways. Mineral deposits need to be discovered, and they can be very difficult to find. Their extent is defined by what is located beneath the ground surface as well as many other factors that are constantly changing. These include demand, commodity prices, available mining, and processing technology, as well as the potential effects of their development, which encompasses a very wide range of factors. Mineral resources are constantly changing because of consumption, exploration, and research defining new resources, and economic and other changes that affect the feasibility of mining and processing minerals.

New Zealand has adopted the Australasian 'JORC' code for reporting mineral resources (JORC 2012), that was developed primarily for reporting to investors or potential investors. It is produced by the Joint Ore Reserves Committee that comprises the Australasian Institute of Mining and Metallurgy, the Minerals Council of Australia and the Australian Institute of Geoscientists. It classifies resources as 'inferred', 'indicated', and 'measured' as the level of geological knowledge and confidence about the resources increases (Figure 10). Parts of indicated and measured resources can be classified as 'proven' and 'probable' reserves

BOX 4

Aggregate facts (Aggregate and Quarry Association)

- On a per capita basis each New Zealander consumes 7–10 tonnes of aggregate (a small truckload) per year.
- For each tonne of aggregate produced, every 30 km it has travelled doubles the cost.
- In Auckland, aggregate is already being transported 100 km or more.
- The radius limit for competitiveness is about 50 km.
- An average New Zealand house contains about 250 tonnes of aggregate.
- About 10 000 tonnes of aggregate is used to build each kilometre of two-lane sealed highway, whereas about 50 000 tonnes are needed per kilometre of new four-lane motorway.
- A typical office building with concrete construction contains about 100 000 tonnes of aggregate.
- There are more than 15 000 road bridges in New Zealand. The typical highway bridge takes about 10 000 tonnes of aggregate to build.

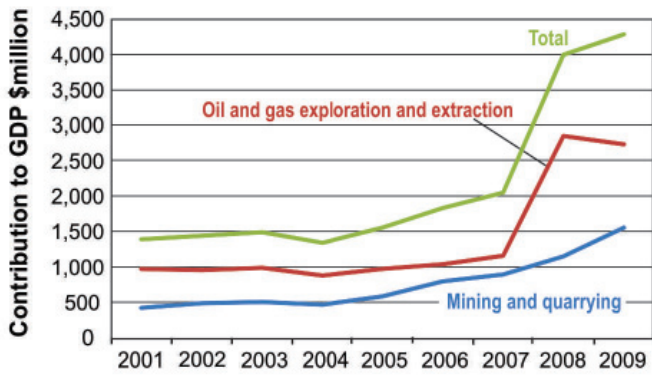


FIGURE 8 Mining and petroleum – contribution to GDP 2001–2009. Source: Statistics NZ.

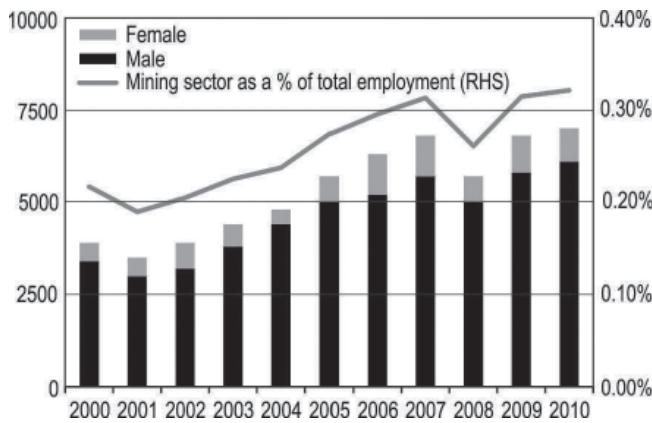


FIGURE 9 Mining employment 2001–2010. Source: Statistics NZ.

TABLE 2 Contribution to GDP of main primary industries. Sources: NZ Petroleum & Minerals, Ministry of Agriculture and Forestry, Statistics NZ (National accounts)

| Sector | Land area (sq km) | Contribution to GDP (NZ\$million for 2009) | Value NZ\$ per hectare |
|------------------------------|-------------------|--|------------------------|
| Production forestry | 18 000 | 999 | 555 |
| Dairy farming and processing | 20 000 | 6,339 | 3,170 |
| Horticulture, viticulture | 1100 | 1,189 | 10,809 |
| Mining excluding petroleum | 60 | 1,554 | 259,000 |
| Petroleum | | 2,731 | |

once a range of economic and other factors (the modifying factors in the figure) are considered.

Coal resources

Published literature on coal resources in New Zealand (e.g. Barry et al. 1988) has used a system of ‘in-ground’ and ‘recoverable’ coal resources and reserves. These categories are not compliant with the JORC code, although the JORC system of reporting reserves and resources is retained. In current resource assessments the JORC code is applied to coal by replacing terms such as ‘minerals’ by ‘coal’, and ‘grade’ by ‘quality’.

Petroleum resources

Oil and gas reserves are defined as volumes that will be commercially recovered in the future, based on the evaluation of data that provide evidence of the amount of oil and gas

present. All such estimates are necessarily uncertain. The reserve and resource system developed by the Society of Petroleum Engineers and used in New Zealand (Figure 11) accounts for this uncertainty by classifying reserves and resources according to the level of certainty of the recoverable volumes (horizontal axis) and the potential for commercial development (vertical axis). Proved, probable and possible reserves are often referred to as P90, P50, and P10 respectively, which refers to the percentage probability of the reserves being developed.

THE GEOLOGICAL SETTING OF NEW ZEALAND’S MINERAL RESOURCES

New Zealand’s mineral potential is determined by its geological history and tectonic setting. New Zealand is located in a geologically active zone at the boundary between the Pacific Plate, which underlies most of the Pacific Ocean, and the Australian Plate that extends under the Tasman Sea, Australia, and the Indian Ocean (Figure 12). As a result of its location at an active plate boundary, New Zealand hosts a number of active volcanoes, areas of geothermal activity, and experiences frequent earthquakes. Past geological activity has produced deposits of gold and other metals, and a range of industrial minerals. During periods of geological stability, extensive peat swamps formed and have subsequently been deeply buried and converted to lignite and coal. Limestone was deposited across New Zealand when much of the country was submerged beneath the sea.

The older rocks of New Zealand comprise three main basement elements formed on or near the margin of Gondwana: the Western Province (Early to Mid-Paleozoic), Eastern Province (Late Paleozoic to Early Cretaceous) and Median Batholith (Mid-Paleozoic to Early Cretaceous) (Figure 1). In the South Island, these three units are displaced into north-west and south-east segments by 480 km of Late Cenozoic movement along the active Alpine Fault. The basement rocks are overlain by Late Cretaceous to Cenozoic sedimentary basins that developed after the separation of New Zealand from Gondwana in the Late Cretaceous (Figures 1, 3 and 13).

The Western Province rocks include metamorphosed sandstone, mudstone, limestone, and volcanic rocks, intruded by granite batholiths and mafic-ultramafic igneous complexes. The main associated mineral deposits (see Box 5) are orogenic gold-quartz veins hosted by Paleozoic greywacke and argillite (e.g. Globe Progress mine at Reefton). Other types of deposits present include: volcanogenic massive sulphide lead-zinc; vein and greisen tungsten and tin; granite-related gold; and magmatic nickel-copper sulphide, platinum group element, and magnetite-ilmenite deposits. Granodiorite stocks, intruded during the Early Cretaceous, have associated porphyry molybdenum mineralisation.

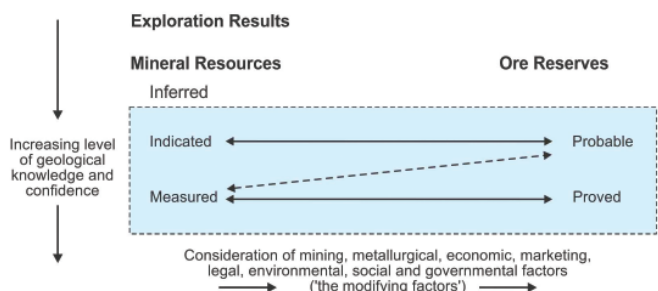


FIGURE 10 JORC classification of exploration results, mineral resources and ore reserves.

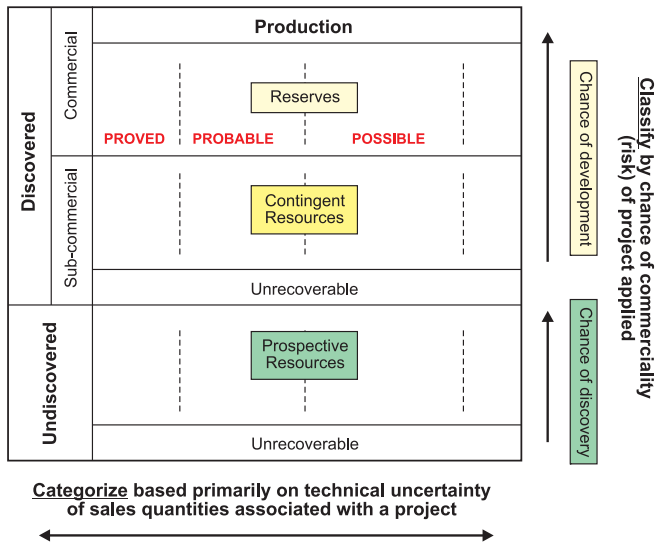


FIGURE 11 Petroleum resources management system. Source: Society of Petroleum Engineers.

The Eastern Province includes the greywacke rocks forming the axial ranges of the North and South islands, and a belt of schists in Marlborough, the Southern Alps and Otago. These rocks host volcanogenic massive sulphide copper deposits and volcanogenic manganese-chert deposits. A belt of Permian ultramafic rocks (Dun Mountain Ophiolite) has associated copper, chromite and chrysotile asbestos mineralisation. Chlorite-zone schists in Otago and Marlborough contain widespread gold ± scheelite ± stibnite mineralisation in shear zones and quartz veins, including the large Macraes deposit in east Otago. Lenses of serpentinite with talc-magnesite and nephrite jade (greenstone or pounamu) occur in ultramafic schists in the Southern Alps.

The Late Cretaceous to Cenozoic sedimentary basins contain New Zealand's economic petroleum, coal and limestone deposits. Gold-bearing quartz gravels associated with Miocene coal measures are widespread in Otago and eastern Southland. The Oligocene–Miocene boundary is marked by the emplacement of allochthonous rocks in Northland and East Cape and the initiation of volcanic arcs in northern New Zealand. The allochthons consist of dismembered Cretaceous to early Cenozoic marine sediments, ophiolitic basalts, and minor serpentinite. The ophiolitic basalts contain volcanic massive sulphide deposits.

From the Miocene, volcanic rocks occur in eastern South Island (e.g. intraplate basaltic volcanoes on Banks and Otago peninsulas) and feature prominently as basalt–andesite–dacite–rhyolite arc volcanoes in the North Island (Northland, Coromandel, Taupo Volcanic Zone and its offshore extension along the Kermadec Arc, and Taranaki). There are economically important volcanic-hosted epithermal gold–silver deposits (Coromandel region), and deposits of halloysite (Northland), zeolite, microsilica, perlite, pumice and native sulphur (Taupo Volcanic Zone). Miocene porphyry copper mineralisation is associated with subvolcanic intrusive rocks in northern Coromandel and in eastern Northland, where lead–zinc skarn mineralisation has also been found. Seafloor massive sulphide mineralisation has recently been discovered at several submarine volcanoes in the southern Kermadec volcanic arc. Erosion of the Taranaki andesite volcanoes and volcanic rocks erupted from the Taupo Volcanic Zone have shed titanomagnetite onto the west coast of the North Island forming significant Holocene to modern coastal and offshore placer deposits.

BOX 5

Mineral deposit classification

Mineral deposits are grouped into a series of types, based on some common characteristics, such as host rocks, form, contained minerals and mode of formation. An explanation of the different mineral deposit types mentioned in this chapter is beyond its scope. The reader is referred to Christie and Brathwaite (1999) for descriptions and explanations.

From the Late Miocene to the present day, large regional uplifts along the Alpine and related fault systems, and subsequent erosion, have formed 'giant' gold placers in riverbed and terrace (glacial outwash) gravels in Westland and Otago. Erosion of garnet schist along the Southern Alps has resulted in the formation of ilmenite–garnet–gold placer deposits along, and offshore from, the west coast of the South Island. Offshore east of the South Island, extensive fields of marine phosphorite nodules are found on the Chatham Rise in water depths of approximately 400 metres. Also offshore, an extensive ferromanganese nodule field occurs at abyssal depths south of New Zealand adjacent to the Campbell Plateau in the south-west Pacific Ocean.

NEW ZEALAND MINERAL PRODUCTION AND RESOURCES

Aggregates

About 26 million tonnes of aggregates were produced in New Zealand in 2011 (Table 1) from several hundred quarries and pits located throughout the country. Aggregate production has declined significantly since a peak of 38 million tonnes in 2005 as a result of a downturn in construction activity. The main users of aggregate are road construction and maintenance, and concrete produced for building (Figure 14).

The production of ready-mixed concrete is checked through a quarterly census of producers by Statistics NZ to monitor

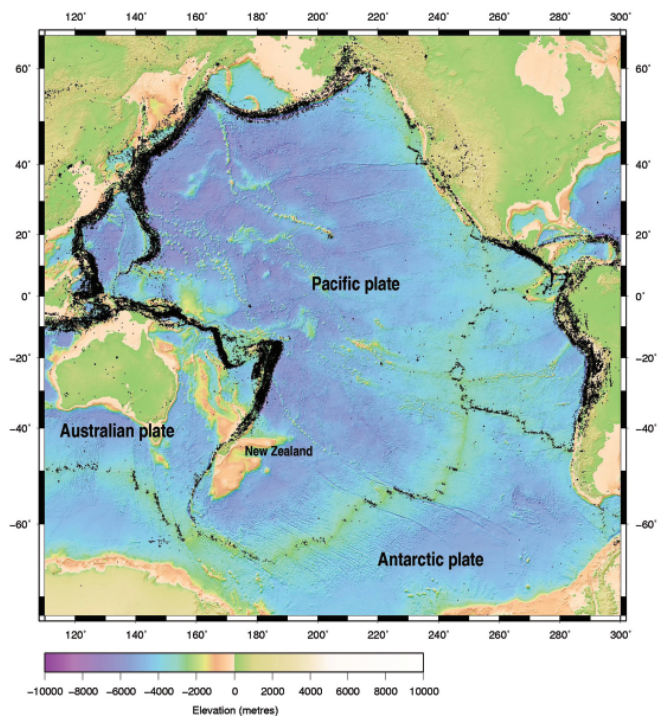


FIGURE 12 New Zealand's tectonic setting. The New Zealand continent of Zealandia is a largely submerged continent with only approximately 5% of its area above sea level. It straddles the boundary between the Pacific and Australian plates in a zone of intense earthquake activity (shown by black dots).

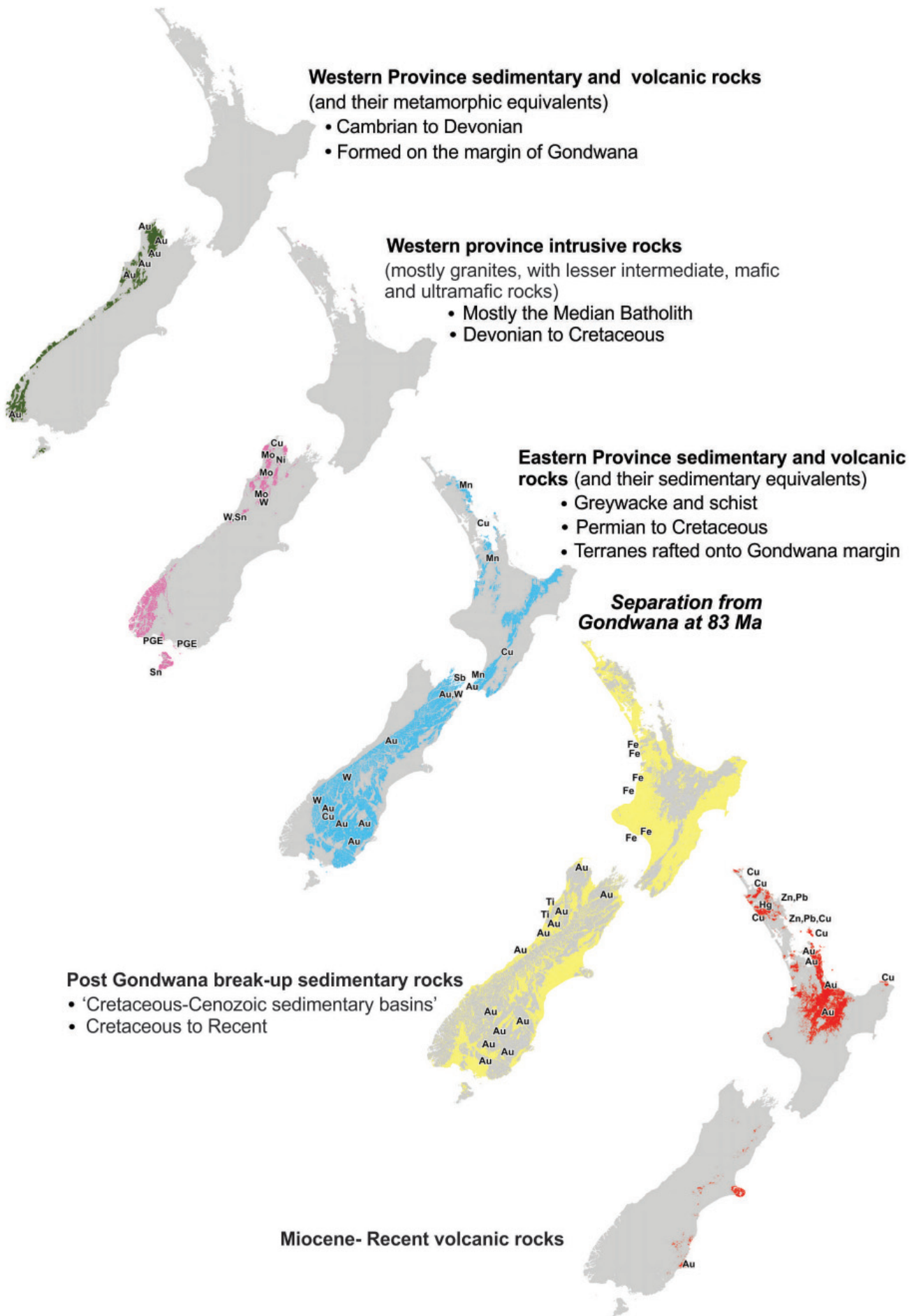


FIGURE 13 Geological evolution of New Zealand and associated metallic mineral deposits. Au = gold, Cu = copper, Mn = manganese, Mo = Molybdenum, Ni = nickel, Pb = lead, PGE = platinum group elements, Sb = antimony, Sn = tin, Ti = titanium, W = tungsten, and Zn = zinc.

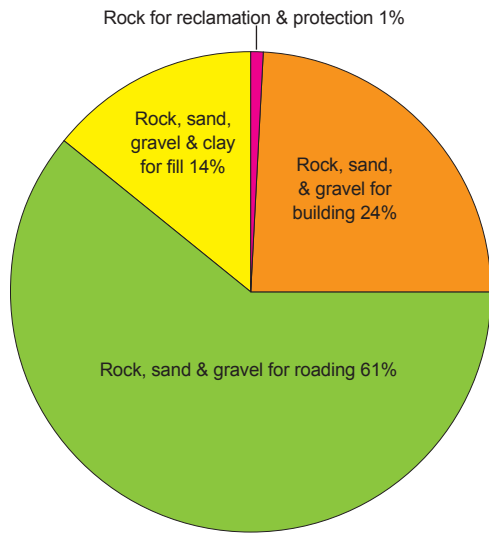


FIGURE 14 Uses of aggregate production 2011. Source: NZ Petroleum & Minerals.

construction activity, a key domestic economic indicator. Concrete consists mainly of aggregate; one cubic metre of concrete typically contains about 2 tonnes of rock aggregate and 0.3 tonne of cement (derived from limestone). Production of concrete reached 1 million tonnes in the first quarter of 2007, but has been at 2002 levels between 2009 and 2011 (Figure 15). Despite the recent decline, concrete production has increased by 100% since 1992. It is now rising again as construction activity picks up. It can be expected to return to past high levels because of demand pressure resulting from population growth and an increase in road maintenance and construction activity.

Aggregates in New Zealand are made mainly from greywacke rocks that underlie much of both islands. These are quarried, or extracted from riverbeds and alluvial terraces where natural transport processes have upgraded their quality through the breakdown of weaker material. Volcanic rocks (andesite and basalt) are used in the North Island, mainly around Auckland and Taranaki, while various other rock types are used in the south of the South Island in locations where greywacke is not available (Figure 16).

Gold

New Zealand gold deposits can be divided into two broad categories: alluvial (placer) and hard rock. Hard rock gold deposits can be further subdivided into several different types, although past and present gold production is from three types (Figure 17):

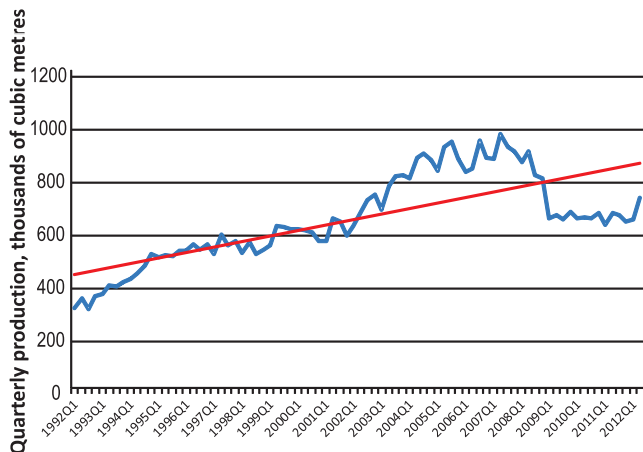


FIGURE 15 Ready-mixed concrete production by quarter. Source: Statistics NZ.

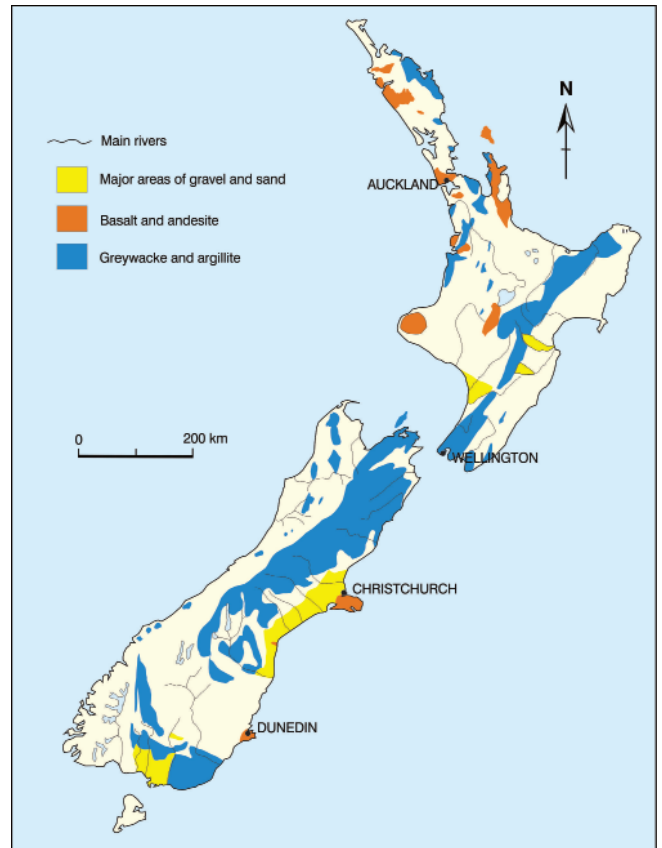


FIGURE 16 Location of main rock types used for aggregate in New Zealand. Source: Christie et al. (2001).

- Orogenic quartz vein deposits in Paleozoic metagreywacke
- Orogenic quartz vein deposits in Mesozoic schist
- Epithermal quartz vein deposits in Cenozoic volcanic rocks.

Other hard rock styles of gold mineralisation represented in New Zealand include porphyry copper deposits that commonly contain gold, silver, and molybdenum; other hydrothermal deposits related to igneous intrusions; and volcanogenic massive sulphide deposits that contain gold and base metals, commonly copper.

Alluvial gold is found as grains of gold and other metals in river gravels that are eroded, transported and concentrated by rivers and, less commonly, glaciers. Placer is a more general term that includes seabed and coastal deposits as well as alluvial deposits. Gold is extracted from these deposits mainly using gravity separation methods (pure gold is 19 times denser than water). Gold in hard rock deposits is encased within rocks. Deposits of this type account for most of the gold produced. Crushing, grinding, and chemical treatment is usually needed to separate the gold from hard rock deposits.

Three hard rock mining areas, Waihi, Reefton and Macraes (Figure 1), account for most of the gold produced in New Zealand, which totalled about 377 000 ounces in 2011, down from 430 000 ounces in 2009 and 2010. The Martha mine at Waihi, 110 km south-east of Auckland in the North Island, works an epithermal gold-silver deposit in an open pit on the former Martha underground mine, and two nearby underground mines – Favona and Trio – have been developed recently by the company. Together these produced 96 000 ounces of gold in 2011.

Reefton and Macraes in the South Island are two areas of orogenic gold deposits worked in hard rock mines. Surface and underground mines at Macraes in Otago have been New Zealand’s

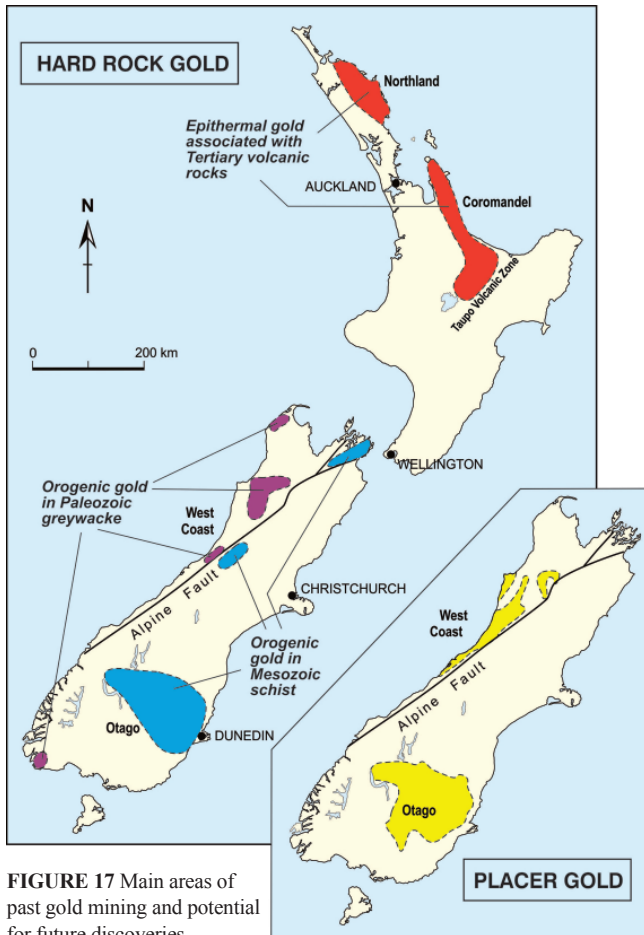


FIGURE 17 Main areas of past gold mining and potential for future discoveries.

See Figures 18, 22 and 25 for more detail on specific gold deposit types.

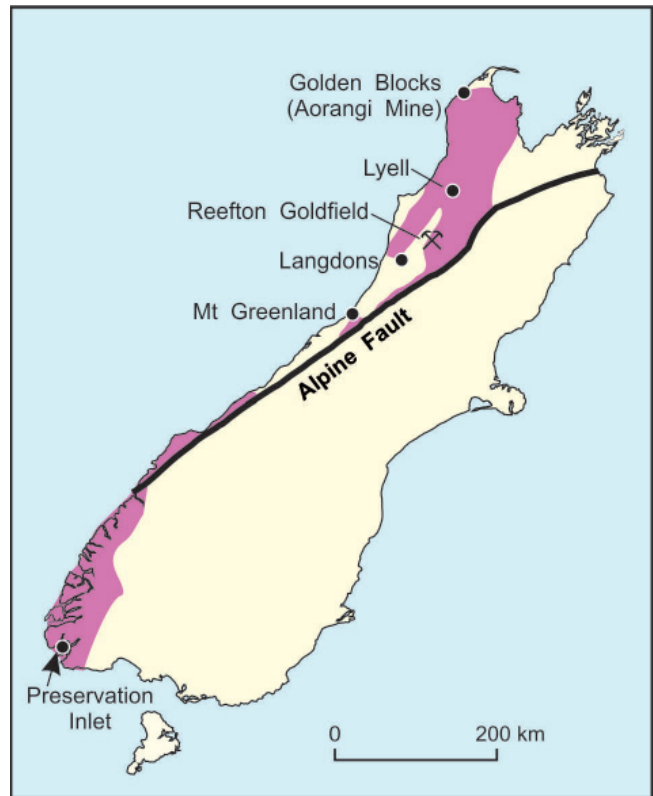


FIGURE 18 Orogenic gold deposits in Paleozoic rocks.

largest producers, and in 2011 gold output was about 177 000 ounces. The Globe Progress hard rock operations at Reefton added about 78 000 ounces to gold output in 2011.

Placer mining contributed a further 26 000 ounces of gold from about 30 operations located mainly on the West Coast of the South Island with some production from the Otago and Southland regions.

Orogenic quartz veins in Paleozoic metagreywacke — Greywacke-hosted orogenic gold deposits are found in Ordovician rocks in the west of the South Island (Figure 18), and have accounted for about 8% of New Zealand’s total gold production. The deposits consist of quartz veins that were formed in steeply dipping shear-and-fault structures in Greenland Group greywacke and argillite. The deposits were probably deposited by hydrothermal fluids released during greenschist facies metamorphism.

The most important deposits of this type in New Zealand are those in the Reefton Goldfield, where over 2 million ounces of gold were produced from 84 mines between 1870 and 1951 from an area about 34 km in length by 10 km wide (Figure 19). Gold predominantly occurs in quartz veins hosted in Paleozoic greywacke (Figure 20). Quartz veins at the Globe Progress mine produced 400 000 ounces of gold between 1879 and 1920. OceanaGold’s open pit mine (Figure 21) commenced operating here in 2007. It produces about 80 000 ounces of gold per year and it is currently being evaluated for potential underground mining.

Orogenic quartz veins in Mesozoic schist — Orogenic quartz vein gold deposits are found in the Haast Schist of Otago, Marlborough, and the Southern Alps (Figure 22). The

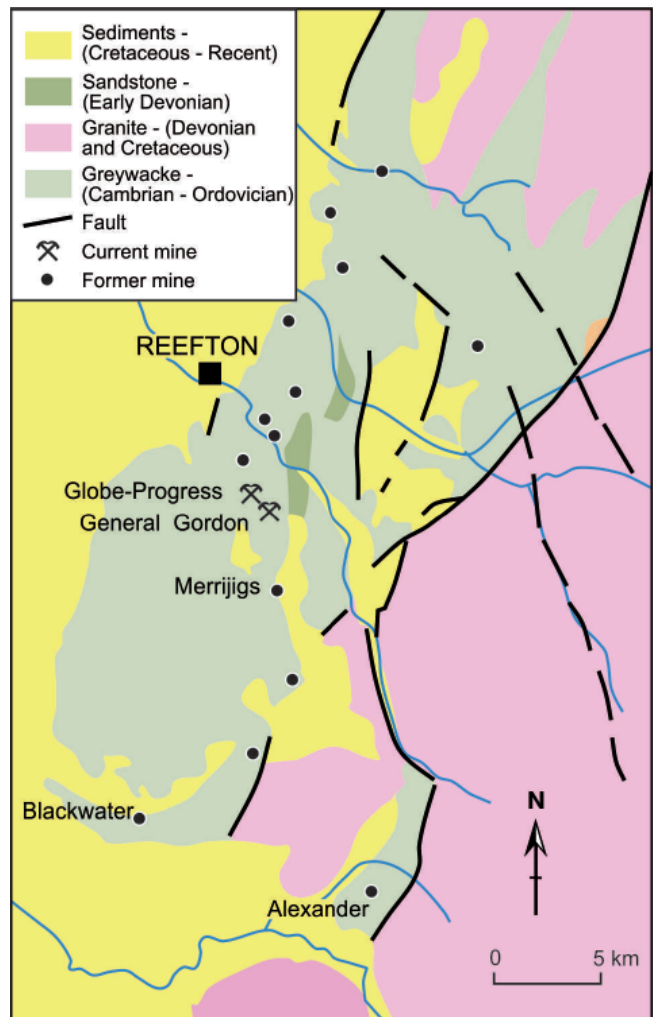


FIGURE 19 Geology of the Reefton Goldfield.



FIGURE 20 Outcrop of the Empress quartz vein south of the Globe mine in the Reefton Goldfield. Photo: Tony Christie.



FIGURE 21 Globe Progress mine near Reefton produces about 85 000 ounces of gold per year. View of the processing plant (right foreground), Globe (right distance) General Gordon and Souvenir pits (left distance), looking south-south-west, February 2010. Photo: Craig McIntosh, OceanaGold

gold-bearing lodes typically occur as lenses, less than 1 m wide and localised along single or multiple parallel shear zones that generally dip steeply. A notable exception is at Macraes mine, where mineralisation occurs in shear veins, stockwork veins and disseminated within the gently dipping (c. 30°) Hyde–Macraes Shear Zone. The shear zone is 26 km long, with gold ore produced from a series of pits along the zone. The current mining operation

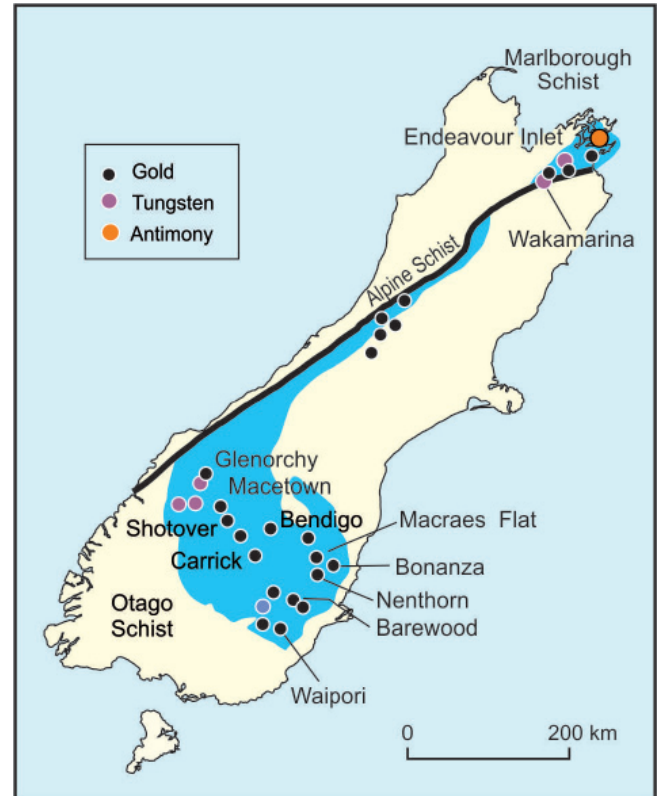


FIGURE 22 Orogenic gold deposits in the Mesozoic Haast Schist of Otago, Marlborough and the Southern Alps.

(Figures 23 and 24) began late in 1990 and the project has now produced more than 2 million ounces of gold.

Although schist-hosted orogenic quartz lodes accounted for only 2.6% of New Zealand's total pre-1980 gold production, the deposit at Macraes Flat is now New Zealand's largest operating gold mine, producing about 180 000 ounces of gold per year.

Epithermal quartz veins in Cenozoic volcanic rocks — Epithermal gold–silver deposits in Northland and in the Hauraki Goldfield were formed in past geothermal systems associated with volcanism that was active in the Miocene–Pliocene. Epithermal gold is being deposited today in active geothermal systems in the Rotorua–Taupo area, in association with Quaternary volcanism.

The Hauraki Goldfield (Figure 25) contains about 50 known epithermal gold–silver deposits that produced about 4.4 million ounces of gold–silver bullion between the 1860s and 1952 (about 34% of New Zealand's total gold production), mostly from vein deposits hosted by andesite and dacite.

The Martha mine is the largest producer in the Hauraki Goldfield with 35 million ounces of gold and silver bullion being produced from underground workings between 1878 and 1952. The mine was reopened in 1988 as an open pit (Figure 26). Four major veins (Martha, Welcome, Empire, and Royal) and numerous smaller veins strike in a north-easterly direction and form a braided vein system over 2.5 km long by 600 m wide extending to a depth of over 600 m (Figure 27). Several other vein systems have also been found in the Waihi area. Historical mining at Union Hill south of Martha focused on the Union and Amaranth veins. Underground mining has been on the Favona and Trio vein systems, both recent discoveries. In 2011, the discovery was announced of the Correnso vein system with a resource of about 600 000 ounces of gold. It is located beneath the town of Waihi and consents for its development are being sought.

Small quantities of ore-grade gold–silver mineralisation have been deposited by geothermal fluids in several active



FIGURE 23 Open pit mining at Macraes gold mine commenced in 1989, followed by underground mining on the Frasers section that commenced in 2008. The mine currently produces about 180 000 ounces of gold per year. Photo: OceanaGold Ltd.



FIGURE 24 Macraes mine, Frasers open pit. The Hyde–Macraes Shear Zone is exposed as a dark grey carbonaceous crush zone dipping to the right on the far wall (above the digger and truck) of Frasers open pit. Photo: Tony Christie.



FIGURE 26 Open pit mining began at the Martha mine in 1988 on the former underground mine (1883–1952), whereas recent underground mining commenced at Favona in 2007 and Trio in 2012 (see Figure 27). Current production from the Waihi mines is about 100 000 ounces of gold per year. Photo: Newmont Waihi Gold.

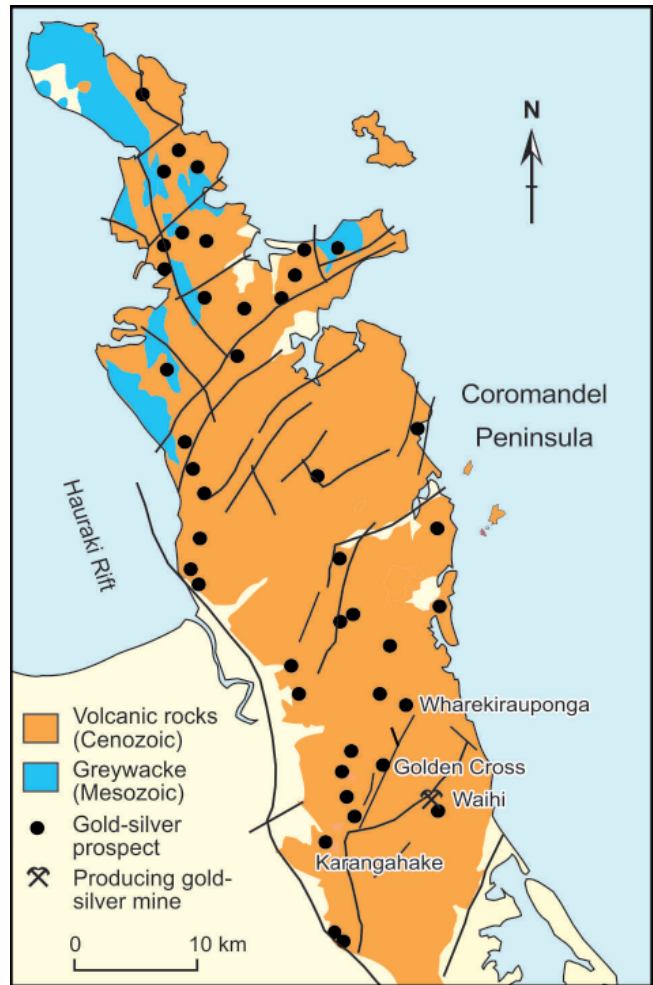


FIGURE 25 Geology of the Hauraki Goldfield.

geothermal fields of the Taupo Volcanic Zone, including Ohaaki (Broadlands), Rotokawa, Waiotapu and Kawerau. Silver–gold mineralisation is also present in fossil geothermal systems in the Taupo Volcanic Zone.

Several hot-springs-type epithermal deposits are known in Northland. Small quantities of silver and mercury have been produced at Puhipuhi, north of Whangarei, and mercury at Ngawha, near Kaikohe. Reconnaissance drilling to intersect feeder quartz veins at Puhipuhi intersected potentially economic gold grades.

Placer deposits — Giant placer gold fields are present in Cenozoic gravel and sand in Westland and Otago–Southland, and smaller placers are found in west Nelson and Marlborough (Figure 17). About 20 million ounces of gold were produced in the past, equivalent to about 54% of New Zealand’s total historical production, initially during the gold rushes of the 1860s and 1870s, and later by sluicing and dredging operations. Since 1980 there have been a large number of small- and medium-scale gold recovery

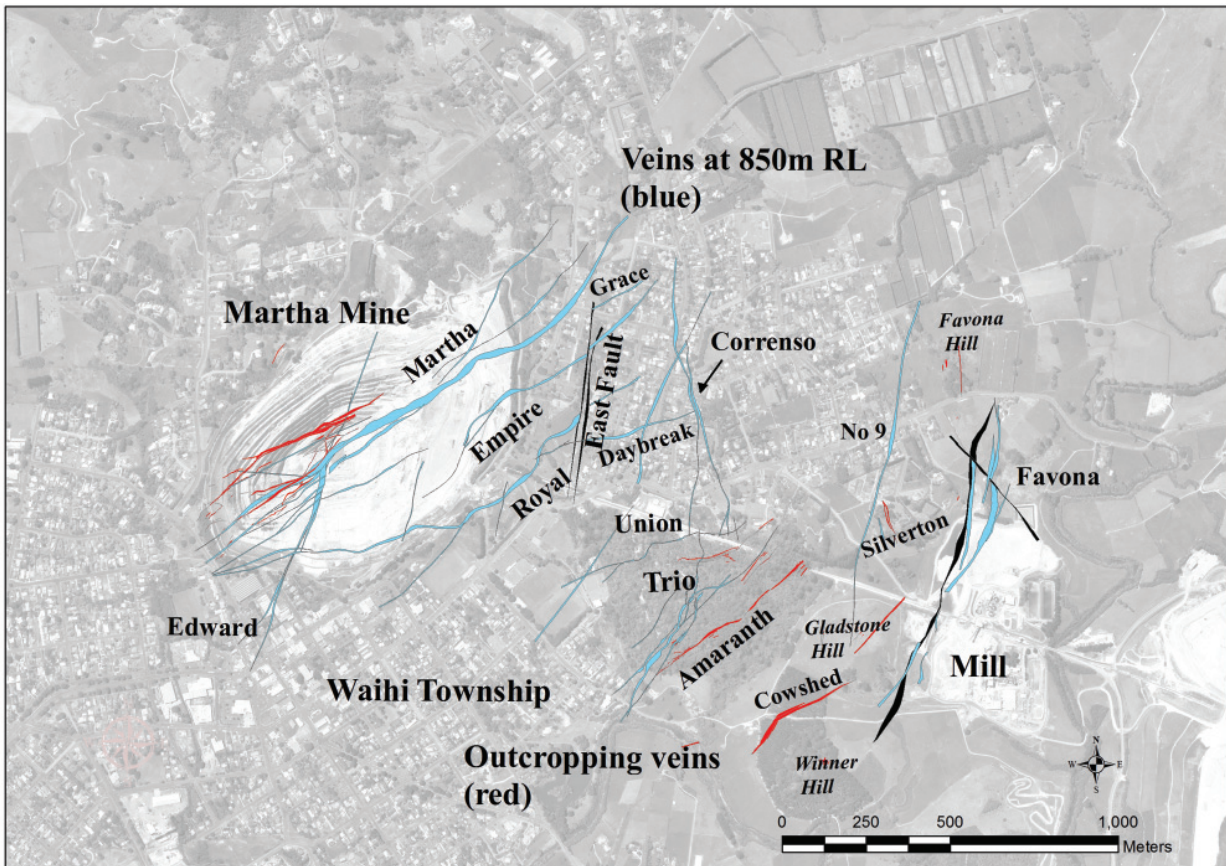


FIGURE 27 Veins in the Waihi area (after fig. 1 of Torckler et al. 2006). They are ~270m below Waihi town.



FIGURE 28 Gold recovery plant on the Arahura River in the 1990s. Photo: Eoin Jury.



FIGURE 29 A bucket-ladder gold dredge that has worked intermittently in the Grey River since 1992.

operations using hydraulic excavators and mobile gold recovery plants (Figure 28). A reconditioned gold dredge has operated intermittently in the Grey River valley (Figure 29).

Beach placers are found on the west and south coasts of the South Island in present-day beaches, older postglacial beach deposits, and the raised beach deposits of successive marine interglacials that underlie the remnants of coastal terraces. Gold is concentrated with other heavy minerals into lenticular beach placers. Offshore deposits of placer gold are present off the Coromandel Peninsula and the West Coast at Hokitika.

Ilmenite

Ilmenite-rich black sands, with locally economic concentrations of gold, occur at intervals along 320 km of the west coast of the South Island. The ilmenite and other heavy minerals (garnet and minor zircon, with traces of monazite and gold) have been derived from erosion of garnet-grade Haast Schist in the Southern Alps. Many of the deposits consist of narrow, elongate Holocene beach and dune deposits, generally parallel to and backing the modern storm beach. In the beach sands, ilmenite has been concentrated by wave action into blacksand leads with average grades of 10–25% ilmenite. In the dune sands, ilmenite occurs in concentrations generally less than 6%.

The two largest deposits, at Barrytown (6.9 million tonnes of ilmenite, Figure 30) and near Westport (5.5 million tonnes of ilmenite), have accumulated in embayments of the coastline where progradation has been protected by resistant headlands of Paleozoic granite or greywacke. These two deposits have been investigated, but not yet developed, as a source of titania (TiO_2)—used widely as a pigment.

Ironsand

New Zealand's very large onshore and offshore ironsand



FIGURE 30 Barrytown Flats, West Coast, South Island, are underlain by sand deposits containing ilmenite and gold. View looking south. Photo: Vivienne Bull.

resources along the west coast of the North Island are worked at Taharoa (near Kawhia) for export and at Waikato North Head south of Auckland to supply the nearby steel mill at Glenbrook. Present production of about 2 million tonnes of ironsand concentrate (about 55% Fe) annually is very small in relation to the potential size of the resources.

These operations work titanomagnetite ironsand placers that form Quaternary onshore beach and dune deposits and offshore marine deposits along 480 km of coastline between Kaipara Harbour and Wanganui on the west coast of the North Island (Figure 31). Quaternary andesitic volcanic rocks of western Taranaki are the main source of the titanomagnetite, which has been concentrated by marine currents, wave and wind action.

Onshore resources have been estimated at about 1.3 billion tonnes of titanomagnetite. Geological modelling of source rocks suggests potential for total resources of about 39 billion tonnes of titanomagnetite (Christie et al. 2009). Exploration of these resources using aeromagnetic surveys and drilling is continuing both onshore and offshore.

At Waikato North Head (Figure 32), ironsand is mined by bucket wheel excavators, and processed to produce a titanomagnetite concentrate slurry that is piped 18 km to the steel mill at Glenbrook. Annual production has been about 1 million tonnes of concentrate since the commencement of mining in 1969. A vanadium-rich slag is separated as a by-product.

At Taharoa, ironsand is mined by dredging beach and dune sand to produce a concentrate averaging 40% titanomagnetite. Annual production has averaged about 1 million tonnes since the operation opened in 1972. The concentrate is slurried through a 3-km-long pipeline to an offshore loading facility for export by ship to Asia.

Waipipi, near Waverley, was mined between 1971 and 1987 using a floating dredge similar to that at Taharoa. During this period, 15.7 million tonnes of concentrate at a grade of 56% iron and 7.8% TiO_2 were recovered from 60 million tonnes of sand, and exported to Japan where it was used for blending in blast-furnace steel production.

Other metals

Geological research has classified more than 600 onshore metallic mineral deposits and occurrences into 25 different

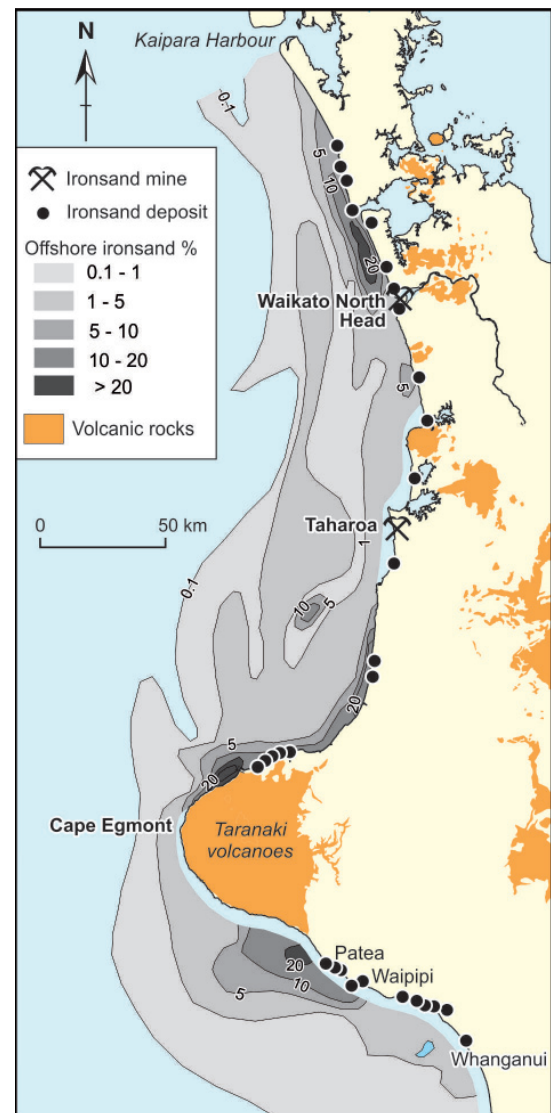


FIGURE 31 Titanomagnetite ironsand deposits and potential source rocks of the western North Island. The titanomagnetite is mainly sourced from erosion of the volcanic rocks of Taranaki, although other volcanic rocks of the central and western North Island may be secondary sources. The contours show the concentration of iron minerals in the upper layer of sea floor sediment. Source: Christie et al. (2009).



FIGURE 32 Waikato North Head ironsand mine. Photo: Tony Christie.

mineral deposit types. Only four of these – epithermal and orogenic hard rock gold, placer gold, and shoreline placer iron-sand – have been worked on a significant scale. In addition to these, New Zealand has produced small quantities of platinum group metals, copper, lead, zinc, tin, tungsten, antimony, arsenic, chromite, manganese, and mercury (Figure 33).

Aluminium — Aluminium is produced from bauxite, which consists of a number of aluminium hydroxide minerals produced by tropical weathering of rocks rich in aluminium silicate. Small deposits of bauxite occur in Northland. Resources of about 30 million tonnes have been estimated in the area between Kaeo, Kerikeri and Kaikohe though alumina (Al_2O_3) grades are low.

Antimony — The main antimony mineral stibnite (Sb_2S_3) has been recorded at many locations around New Zealand in a range of deposit types. Antimony has been produced on a small scale from quartz veins at Rangitaroe Hill in Northland and Endeavour Inlet in Marlborough.

Chromium — The main occurrences of the chromium mineral chromite ($(\text{Mg,Fe})\text{Cr}_2\text{O}_4$) are in ultramafic rocks of the Dun Mountain Ophiolite Belt in east Nelson and northern Otago. About 6000 tonnes of chromite were produced in the 19th century from Dun Mountain, south of Nelson.

Copper — Copper occurrences in five deposit types have been recognised and are recorded from many parts of New Zealand (Figure 1). Modest production is recorded from massive sulphide deposits in Northland and Kawau Island, a porphyry copper deposit on Great Barrier Island, and an epithermal deposit in the southern Coromandel region (Tui mine; see below).

Lead-Zinc — Lead-zinc is recorded in four deposit types in Northland, the Coromandel region, Nelson and Fiordland. The only significant producer has been the Tui mine near Te Aroha in the North Island, which operated between 1967 and 1973, producing 7755 tonnes of concentrate containing lead, zinc and copper and small amounts of gold and silver.

Manganese — Manganese oxide ore has been produced in small quantities from sedimentary deposits in Northland and Auckland. Recorded production totals about 26 000 tonnes of manganese ore.

Mercury — The mercury mineral cinnabar (HgS) has been recorded at many locations in both islands. Small production is recorded from the Ngawha hot springs near Kaikohe and Puhipuhi in Northland, and Mackaytown near Paeroa in the Coromandel Peninsula.

Molybdenum — Molybdenum related to intrusive rocks has been recorded from numerous localities in Nelson and northern

Westland that have been investigated by drilling, although no production is recorded. The main molybdenum mineral molybdenite (MoS_2) is also reported from gold prospects and mines in the Coromandel region.

Nickel — Nickel has been found associated with mafic intrusive rocks in the Nelson and Marlborough regions although no production is recorded.

Platinum Group metals — In New Zealand, platinum group elements (PGE) occur in three main geological environments: layered mafic igneous complexes, ophiolites (derived from sub-oceanic rocks), and in association with placer gold deposits. The PGE metals are platinum (Pt), palladium (Pd), iridium (Ir), osmium (Os) and ruthenium (Ru). Past production of PGE has been the recovery of small quantities in the late 1800s and early 1900s as a by-product of placer gold mining in Southland.

Prospects in Nelson, Kaikoura and Southland have been investigated (Figure 34), so far without success, though PGE minerals have been recorded in outcrop and drillcore. Limited drilling at Longwood (Southland) and Riwaka (Nelson) prospects has given encouraging results for platinum, palladium, and nickel.

Rare earth elements — In New Zealand, rare earth element geochemical concentrations and minerals (e.g. monazite – $(\text{Ce, La, Y, Th})\text{PO}_4$) are found associated with igneous rocks in Nelson, Westland, Fiordland and Stewart Island. Some of these occurrences are being investigated at present, particularly in alkaline granites and carbonatites. Monazite is found in heavy mineral concentrates in ilmenite-bearing sands on the west coast of the South Island.

Silver — The epithermal gold-silver deposits of the Hauraki goldfield have produced much more silver than gold, and are the main source of silver production in New Zealand. Silver also occurs in association with other metals, particularly lead-zinc and copper.

Tin — Tin, occurring as cassiterite (SnO_2), is recorded in hard rock and alluvial deposits associated with granitic rocks on the Tin Range of Stewart Island, and associated with tungsten in vein deposits in Westland.

Titanium — The main titanium minerals are ilmenite (an iron-titanium mineral, FeTiO_3) and rutile (TiO_2). The ilmenite-bearing beach sands of Westland are the largest known potentially economic ilmenite deposits in New Zealand. These are described above. Ilmenite occurs with magnetite in magmatic rocks at several locations in the South Island including Nelson, Kaikoura, Westland and Fiordland. The ironsand mineral titanomagnetite contains titanium, but this is currently not separately recovered during the iron and steel making, and mostly ends up in the slag.

Tungsten — In New Zealand, tungsten occurs mainly as scheelite (CaWO_4) in a range of deposit types, but mainly in quartz-scheelite-gold veins in Otago and Marlborough. It also occurs in quartz veins associated with granite in Nelson, Buller and Westland. Wolframite ($(\text{Fe,Mn})\text{WO}_4$) accompanies the tin mineral cassiterite on the Tin Range of Stewart Island.

Uranium — Known hard rock uranium is confined to occurrences hosted in sedimentary rocks at localities in the Buller Gorge and Pororari River on the west coast of the South Island. Uranium minerals have also been recorded from West Coast gold dredging concentrates.

Non-metallic industrial minerals

With a population of 4.4 million, New Zealand's market for industrial minerals is confined to relatively large quantities of building materials for new construction, and fertiliser minerals

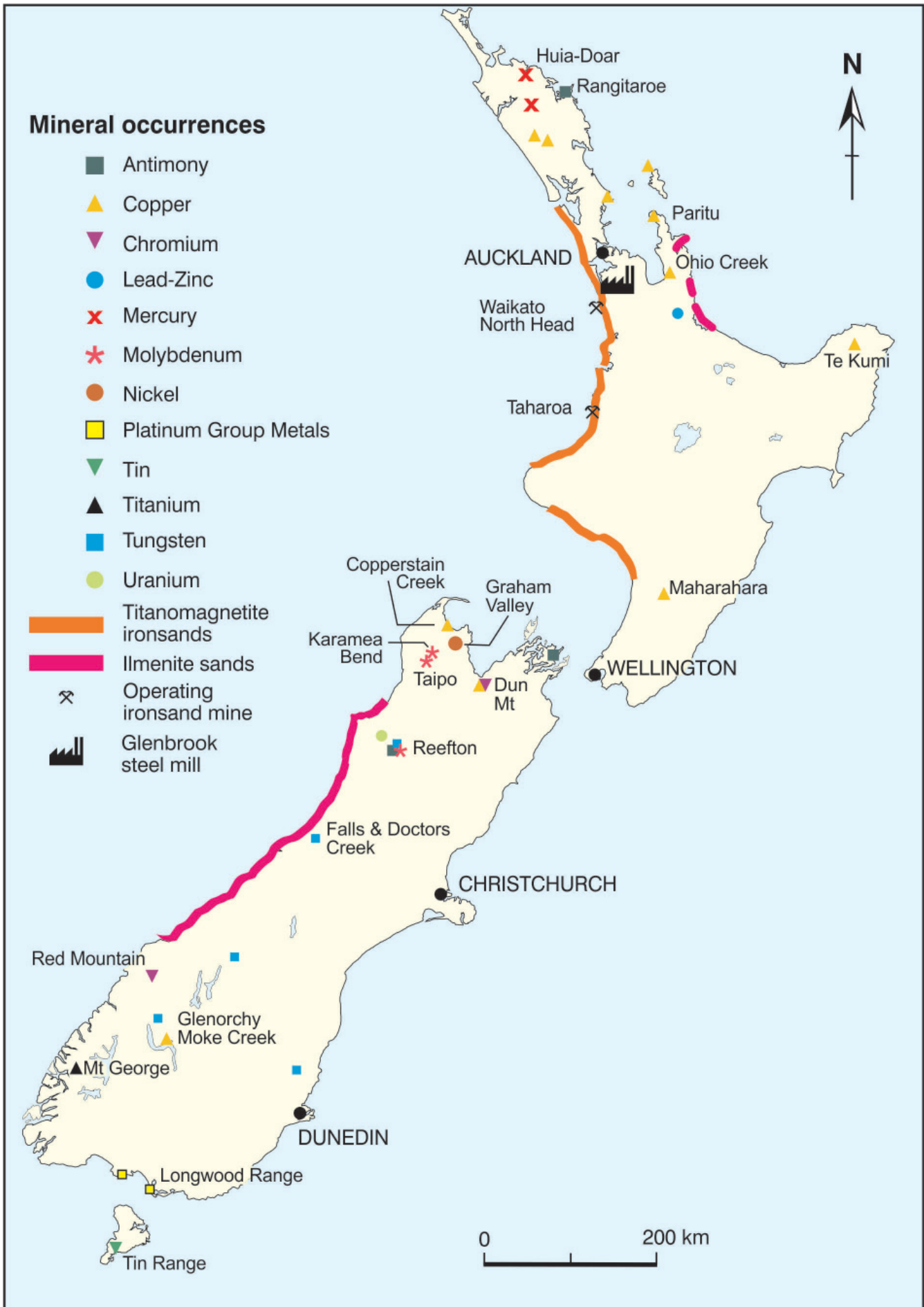


FIGURE 33 Locations of metallic mineral occurrences, excluding gold.

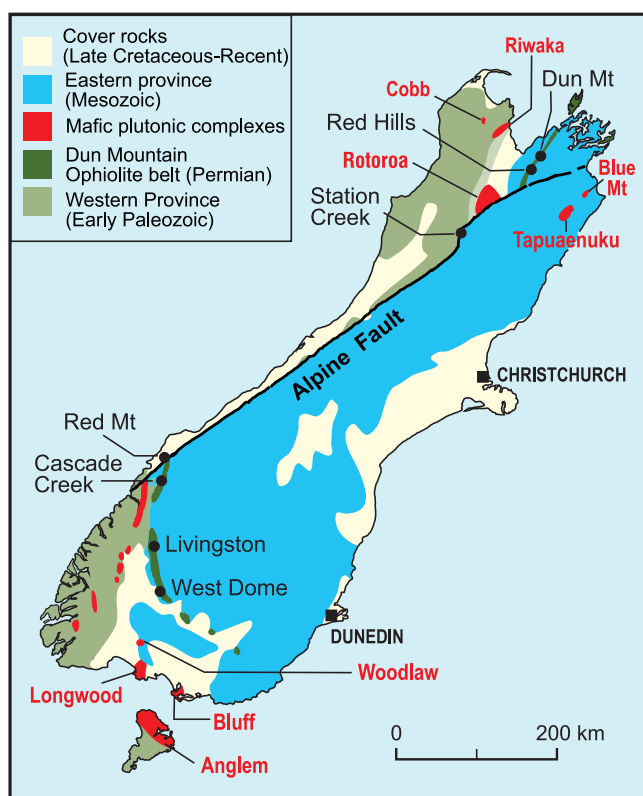


FIGURE 34 Platinum group element prospects, South Island. Red location labels are layered mafic igneous complexes, whereas black prospect location labels are mafic igneous rocks of the Dun Mountain Ophiolite Belt.

for the high level of agricultural production. On a per capita basis, New Zealand is the world's largest consumer of phosphate rock, potash and sulphur for use in agricultural fertiliser.

New Zealand produces a diverse range of industrial minerals (Table 1 and Figure 35). Industrial minerals produced in 2011 included limestone for making cement, for agriculture and a range of industrial uses; bentonite clay mainly for export; halloysite clay for export; kaolinite clay for making bricks for pottery and ceramics; dolomite and serpentinite for agriculture; silica, which has a range of uses; and zeolite, which is an absorbent used for decontamination and for making pet litter. Output of most commodities is governed by domestic demand. Because of New Zealand's distance from markets, export products must have properties that give them an international market.

Currently New Zealand's main industrial mineral exports are ironsand, halloysite clay, lime, limestone and cement. Minor export items include peat, salt, sulphur and pumice. The main minerals imported into New Zealand are fertiliser minerals such as phosphate, potash and sulphur; gypsum for use in plaster and cement manufacture and refractory clays; magnesia; building stone; magnesite; talc; diatomite; and specialised cement. Figure 35 shows the main industrial mineral deposits and occurrences.

Limestone — Limestone is a sedimentary rock composed primarily of calcium carbonate (CaCO_3) in the form of the mineral calcite. Limestone deposits are widespread throughout New Zealand (Figure 36). Limestone containing more than 70% CaCO_3 is used for agricultural fertiliser and for roading aggregate. High grade limestone and marble suitable for domestic and export industrial use are widespread. The best quality large tonnage deposits, containing 97.4–99.5% CaCO_3 , are present in the south Waikato near Te Kuiti, where limestone is produced for a wide range of industrial uses and for making burnt lime. High quality limestone is used domestically as a filler in paper, plastics,

paint and rubber, for paper surface coatings, and in glass making.

Uses of burnt lime include steelmaking at the Glenbrook mill, in processing gold ore at the Martha Hill gold mine at Waihi, at Macraes in Otago, and offshore at Lihir (Papua New Guinea) and at Gold Ridge (Solomon Islands). Domestic uses also include pulp and paper manufacture at the Tasman and Carter Holt Harvey paper mills, in the sugar industry, in soil stabilisation, and in sewage sludge and wastewater treatment.

Limestone for agricultural use is produced at more than 50 quarries throughout New Zealand.

Cement — New Zealand has two cement manufacturing plants, one at Portland, near Whangarei, operated by Golden Bay Cement Company, and the other at Cape Foulwind, near Westport, operated by Holcim New Zealand. The domestic market is the principal consumer of the cement products, although some is exported to the Pacific Islands. The cement works use local limestones mixed with marl (calcite-bearing mudstone) for their feed. Holcim is investigating a new cement plant at Weston near Oamaru to replace the West Coast operation.

Marble — Marble is a recrystallised (metamorphic) form of limestone. The Ngarua quarry, located 15 km north-west of Motueka, Northwest Nelson, is operated by Ravensdown and has been producing marble with a calcium carbonate content greater than 98.6%. The product is used as a filler, for surface coating, and for agricultural lime.

Dolomite — Dolomite is produced from a quarry on Mt Burnett, in Northwest Nelson. It occurs as discontinuous lenses in a folded dolomite–marble sequence. The dolomite is 60–70% CaCO_3 , 28–39% MgCO_3 , with up to 3% SiO_2 and up to 0.66% Fe_2O_3 . It is used as a source of magnesium and as a building material including the exterior of the Te Papa museum in Wellington.

Halloysite — Halloysite clay, reputed to be 'the world's whitest clay', is produced from deposits at Matauri Bay, 100 km north of Whangarei in Northland, by Imerys Tableware NZ (Figure 37). The clay is formed by subtropical weathering of Pliocene to Pleistocene age rhyolite to produce a raw material comprising approximately 50% halloysite, 50% silica and minor feldspar. Halloysite produced from clay deposits at the Matauri and Mahimahi rhyolite domes near Matauri Bay is exported to more than 20 countries for the manufacture of high-quality ceramics, principally porcelain, but also fine bone china and technical ceramics.

Kaolinitic clay — Kaolinite clays are used widely for domestic brick, tile, pipe, ceramics and pottery manufacture. Some kaolinite is also used as a filler in rubber, bitumen and adhesives. The largest brick-making operation is the Auckland plant operated by Monier Bricks, a subsidiary of CSR Building Materials (NZ). Clay is sourced from clay pits in the Auckland Region. Small quantities of clay are produced in the Waikato, Bay of Plenty, Nelson and Canterbury regions.

Bentonite — Bentonite, deposited in a freshwater environment during the Late Cenozoic, is mined by Transform Minerals (NZ) in the Harper Hills near Coalgate, 65 km west of Christchurch. Non-swelling calcium bentonite is treated with soda ash to impart swelling properties. Coalgate bentonite is used for paper-making, as a drilling mud, as a growing medium, a stock feed additive, for sealing ponds and reservoirs, and for treating wastewater and effluent. Marine bentonite of Cretaceous age is widespread along the east coast of both the North and South islands.

Silica sand — Silica sand of Quaternary age forms dune, beach and shallow offshore marine sand deposits along the present-day coastline. The main localities are in Northland, at Parengarenga

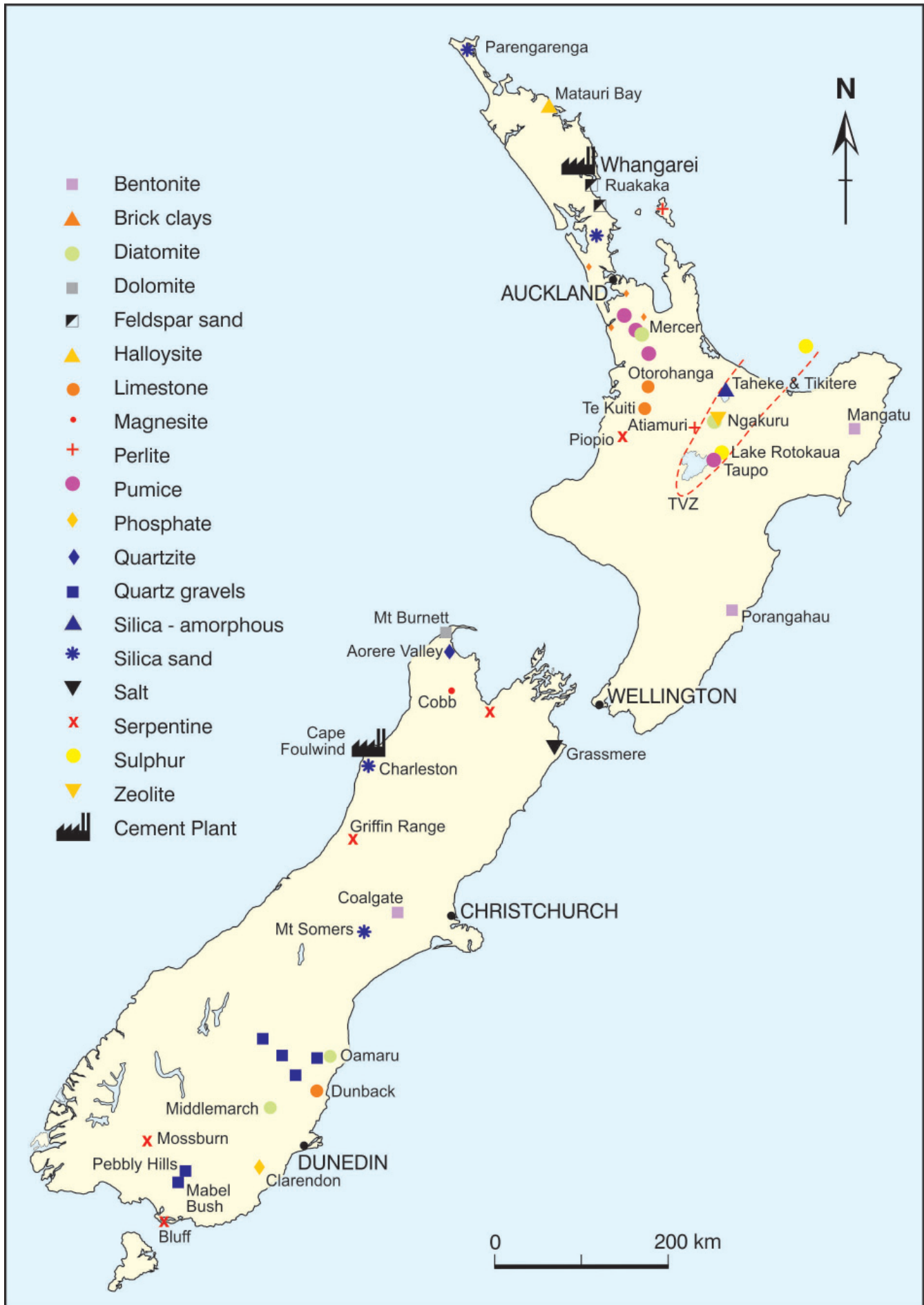


FIGURE 35 Locations of industrial minerals.

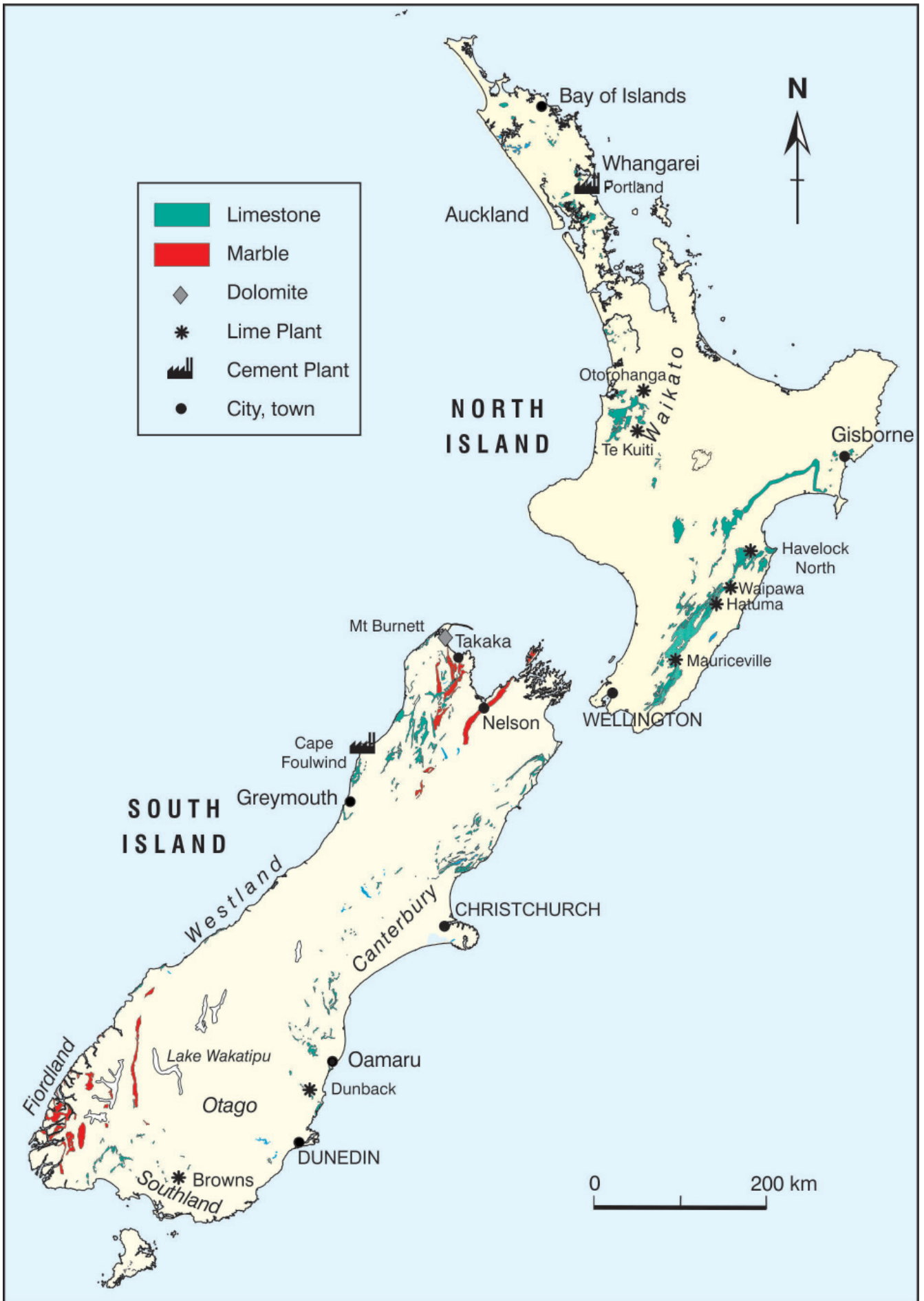


FIGURE 36 Locations of limestone, marble and dolomite deposits.



FIGURE 37 Matauri Bay halloysite clay mine in Northland. Photo: Imerys Tableware NZ Ltd.

Harbour on the east coast and around Kaipara Harbour on the west coast. There are probably more than 80 million tonnes at Parengarenga Harbour, and possibly 10 million tonnes in the Kaipara Harbour area. In the past, about 40 000 tonnes per year of sand were dredged from Parengarenga Harbour and processed into glass at a plant in Auckland.

Silica sands are also concentrated on erosional land surfaces associated with coal measures in the South Island. The main occurrences are at Mt Somers in Canterbury and at Charleston in Westland. There are other deposits in East Otago and Southland.

The several million tonnes of sand at Charleston contain mica (10%) and feldspar (30%), which makes it unsuitable for glassware, but it has been used locally in cement making.

Quartzite — Quartzite formed by metamorphism of quartz sandstones occurs in greywacke in eastern Northland, where there are extensive deposits containing 90–93.7% SiO₂, and in Northwest Nelson, where about 1 million tonnes of ferrosilicon-quality quartzite containing 97–97.6% SiO₂ is associated with schist at Aorere.

Quartz gravels — Quartz gravels in Southland are widespread and have potential for use in the production of ferrosilicon or silicon metal. The quartz gravels around Pebbly Hills – Mabel Bush, in central Southland, were prospected in the early 1970s and further evaluated in 1990–91. The deposits are inferred to contain more than 350 million tonnes averaging 98% SiO₂. Of this amount, 30–40% is suitable for use in ferrosilicon production. The availability of abundant low-ash coal and hydro-electricity are other factors favourable to a ferrosilicon industry in Southland. Similar deposits occur elsewhere in Otago and northern Southland.

Amorphous silica — In the Taupo Volcanic Zone, amorphous silica is forming through acid sulphate alteration in the near-surface parts of active geothermal systems resulting in the conversion of all minerals, except primary quartz, to a low density, white, porous rock composed primarily of amorphous silica and residual quartz crystals. The Tikitere deposit near Rotorua is currently being mined by Microsilica New Zealand to produce a cement additive that reduces the permeability of concrete, making it more resistant to chemical attack and increasing its strength.

Zeolite — The Taupo Volcanic Zone hosts several large zeolite deposits formed by hydrothermal alteration of suitable rocks such as vitric tuffs. A large occurrence is at Ohakuri, where glass within the Ohakuri ignimbrite and younger pyroclastics has been hydrothermally altered to the zeolites mordenite and clinoptilolite, as well as smectite and opal.

Pacific Blue Minerals produces 5000 tonnes per year of zeolite

from deposits discovered in the 1990s at Ngakuru, about 20 km south of Rotorua. A further five large deposits have been identified in the area.

The channel-like, three-dimensional crystal structure of zeolites provides a large surface area for chemical exchange reactions and adsorption of various materials. Each of the zeolite deposits quarried at Ngakuru has unique characteristics. They are specifically suitable as adsorbents and absorbants for soaking up oil/chemical spills, as cat and animal litters, as a stockfeed additive; for water softening, waste and potable water treatment, sports turf and potting mix amendment, and as odour adsorbents and cosmetic additives.

The company has produced a modified zeolite (Aqual-P) that has been used in trials at Lake Okaro near Rotorua to absorb phosphate and nitrogen nutrients and to control the growth of algal blooms that affect aquatic life. Trials to improve its performance are continuing.

Other occurrences of zeolite in New Zealand are known from Southland, and in Northland and Auckland.

Diatomite — Diatomite is a biogenic rock formed from the skeletal remains of diatoms – single-celled algae. Diatomite has been quarried on a small scale from several deposits for use as a mild abrasive, insulation, filtration, and pozzolan material. Two types of deposits are known: lake bed and marine. Diatom-rich lake deposits are interbedded with young volcanic sediments in Northland, Auckland, South Auckland, Waikato and Rotorua. A deposit at Mercer, South Auckland, is estimated to contain about 180 000 tonnes of extractable diatomite and pumicite. At Ngakuru, in the Waikite Valley, 20 km south of Rotorua, diatomite beds have an aggregate thickness of 30 metres and contain medium to high grade diatomite. Drilling in 1998 delineated about 3.5 million cubic metres of diatomite in a central mining block.

At Middlemarch in Otago, diatomite lake deposits are more than 35 m thick. Resources are estimated at about 5 million tonnes. The marine deposits near Oamaru cover an area of about 26 square kilometres and contain diatom-rich beds up to 9 metres thick. These extensive deposits have been worked, principally for use as pet litter.

Perlite — Large resources of perlitic rhyolite of Quaternary age occur as near-surface layers on rhyolite domes, and as flows of perlitic, glassy rhyolite lava in the Rotorua–Taupo area and on Great Barrier Island. Perlite is quarried near Atiamuri, southwest of Rotorua, at two locations, and is processed by crushing, screening and heating to 900°C, to expand the perlite by 7–20 times. It is used in the domestic market as an inert insulator and filler, and for horticultural pot-plant mixes.

The high expansion capacity of perlite from the Taupo Volcanic Zone, which results partly from its young age, makes it particularly good for filtration applications. There is potential for developing this market.

Pumice — Pumice is quarried from very large pyroclastic deposits of Quaternary age in the Taupo Volcanic Zone and dredged with sand from alluvium in the lower reaches of the Waikato River. The main uses of pumice are as fill in road construction, for sand in concrete block manufacture, and for foundations and drainage. It is also used in horticultural soil mixes and is exported for use in the stone washing of denim clothing.

Phosphorite — Phosphorite has been mined at Clarendon, south of Dunedin, where phosphorite-rich beds are found near the top and bottom of the 40-metre-thick Clarendon Sand. Remaining resources are about 5 million tonnes grading 11% P₂O₅. There

is potential for a combined phosphate and glauconite operation provided suitable processes and markets can be developed.

Investigations of offshore phosphorite deposits on the Chatham Rise east of Christchurch are described in the section on offshore minerals.

Sulphur — Deposits of native sulphur are associated with present-day and fossil geothermal areas at Ngawha in Northland and in the Bay of Plenty and Rotorua–Taupo areas. Main areas of past production are White Island, Tikitere, Lake Rotorua and Lake Rotokawa. There is currently no significant production.

Serpentinite — Small quantities of serpentinite are mined and crushed for use as an additive to superphosphate fertiliser to supply magnesium and to assist in the freerunning properties of fertiliser required for aerial topdressing. At Piopio, 100 km south of Hamilton, diapiric serpentinite bodies, up to 1 km in length and 60 metres in width, are emplaced vertically along the Waipa Fault. Rorison Mineral Developments produces serpentinite at Aria near Piopio. The serpentinite is used as a fertiliser additive. Some serpentinite has been used as ornamental stone.

Salt — Although there are no natural bedded salt deposits in New Zealand, salt is produced by Dominion Salt at Grassmere, south of Blenheim, by solar evaporation of sea water. Low rainfall, high sunshine hours and adequate wind assist in the evaporation of the sea water with a resulting salt production of about 60 000 tonnes per year. The company supplies raw solar and vacuum-dried salt to the domestic market for use in chlorine manufacture, edible salt, water treatment, tanning, dairy and agricultural usage.

Feldspar — Plagioclase feldspar-rich dune, beach and marine sands of Quaternary age are found at Ruakaka and Mangawhai, both south of Whangarei, and near Kaipara Harbour. The Ruakaka deposit consists of feldspar (67%), quartz (25%), iron-rich minerals (4%), and rock fragments (4%). The northern end of Ruakaka is estimated to contain 50 million tonnes of sand, which would yield, at 60% recovery, 30 million tonnes of saleable minerals. At the southern end there is probably in excess of 350 million tonnes of sand.

Magnesite — Magnesite occurs along with talc in ultramafic rocks in Northwest Nelson, Westland, North Otago and Southland. At Cobb, south of Takaka in the Nelson Region, 21 802 tonnes of magnesite were produced up to the cessation of mining in 1981.

Pounamu or greenstone — New Zealand greenstone and New Zealand jade are common terms for the mineral nephrite found in western South Island and formed by the metamorphism of the contact zone between schist and ultramafic rocks or magnesium-rich carbonates. Pounamu, the Māori term for greenstone, includes a wider variety of rocks: both nephrite and bowenite (a serpentine mineral). Pounamu was used by Māori for jewellery, tools (e.g. adzes, chisels, gouges and knives for carving and cutting wood, and fish hooks) and weapons (e.g. mere clubs and points for spears), and has strong cultural and spiritual significance. Modern use is mainly for jewellery and ornaments. Ownership of pounamu was vested with Ngāi Tahu in September 1997 as part of their Treaty of Waitangi claim. Māori recognise three main varieties of nephrite on the basis of colour and texture, namely kawakawa, kahurangi and inanga. Bowenite is known to Māori as tangiwai.

Most greenstone has been recovered as river boulders from the West Coast, especially from the Arahura, Taramakau, and Hokitika rivers and their tributaries, although some has also been recovered from glacial boulders (e.g. Cascade Plateau). In several localities, however, nephrite has been located in outcrops within

the Pounamu Ultramafics belt.

Geothermal minerals

Several investigations have been made into the feasibility of artificially precipitating minerals from geothermal water presently used in geothermal electricity generation. These have included the removal of silica from geothermal water for filler and coating applications in high quality inkjet and laser printing paper where its small size, in the order of 0.4 microns, has advantages in its light-scattering and oil adsorption properties, and its use as a flattening agent in paints.

Coal

Coal production — Coal production in the North Island is dominantly of sub-bituminous coal for use by New Zealand Steel at Glenbrook for steelmaking, for electricity generation and for industrial use. Most South Island production is higher rank bituminous coal that is exported. Coal exports have doubled to 2.7 million tonnes between 1996 and 2006, but declined to 2.1 million tonnes in 2011. The export value of coal has exceeded NZ\$500 million per year since 2005. Opencast mines account for about 80% of output with underground mines producing 20%.

Total coal production was less than five million tonnes in 2011, down 7% from 2010. Most coking coal is produced by the opencast Stockton mine in the Buller district from a field that has now produced 50 million tonnes of coal over the last 110 years. A new coking-coal mining operation is proposed at the opencast Escarpment mine in the Buller district on the West Coast and is expected to increase coal production progressively to about 4 million tonnes per year.

Recent investigations have looked at developing the Southland lignite resources with a variety of projects including the production of liquid fuels and fertiliser. Several of New Zealand's coalfields are being investigated for coal seam gas and underground coal gasification.

Coal resources — New Zealand's coal resources have been investigated in detail by a government-funded survey and more information is available on them than for the other resources (Barry et al. 1988). Coalfields occur in both the North and South islands (Figure 38), and resources are summarised in Table 3.

TABLE 3 Summary of the in-ground coal resources of New Zealand. Note: Only the lignite tonnages are likely to meet current standards for defining recoverable resources

| Coal region | Coal rank | In-ground resource (million tonnes) | Recoverable resource (million tonnes) |
|--------------------|--|-------------------------------------|---------------------------------------|
| Northland | Sub-bituminous | 3 | - |
| Waikato | Sub-bituminous | 2100 | 700 |
| Taranaki | Sub-bituminous | 380 | 170 |
| Total North Island | | 2483 | 870 |
| Nelson | Sub-bituminous | 2 | - |
| West Coast | Bituminous, sub-bituminous and lignite | 980 | 340 |
| Canterbury | Lignite | 4 | 2 |
| Otago | Lignite and sub-bituminous | 2700 | 1220 |
| Southland | Lignite and sub-bituminous | 9400 | 6300 |
| Total South Island | | 13 086 | 7842 |



FIGURE 38 Coal regions and main coalfields.

New Zealand has large resources of lignite – a low rank coal – in Otago and Southland. These amount to more than 7000 million tonnes and are New Zealand’s largest conventional energy resource.

Petroleum

Figures 39 and 40 show the production history for oil and gas since 1970. All New Zealand’s oil and gas production comes from the Taranaki Basin (Figure 41). Gas is currently produced from 14 fields, with the majority coming from two offshore fields: the recent Pohokura development and the mature Maui field.

The two newest offshore oil fields, Tui and Maari, have boosted oil production in recent years. Together they contributed 49% of New Zealand’s oil production in 2010, while Pohokura contributed a further 22%. In total, 16 fields in the Taranaki Region produced 19.3 million barrels of crude oil (116 Petajoules (PJ)) and 0.157 trillion cubic feet of gas (173 PJ) in 2010.

Figure 42 compares New Zealand’s primary energy supply in 2011 with the supply 20 years earlier in 1991. In 2011 oil, gas and coal contributed 60% of the total primary energy supply, down from 70% in 1991. The main change has been the expansion of geothermal energy and the decline in the gas supply, with production from the Maui field declining. The proportion of total supply provided by coal, hydro and other renewables has changed by 2% or less. Overall annual energy supply increased by a third between 1991 and 2011, from 617 to 818 petajoules.

The onshore area of New Zealand accounts for about 5% of the largely submerged continent of Zealandia. Therefore there is immense potential for exploration of the 95% of submerged Zealandia. Petroleum occurs in sedimentary basins of Late Cretaceous to Cenozoic age (Figure 3) that are mainly offshore. The Taranaki Basin is partly onshore, and successful onshore exploration here led to the discovery of the Kapuni gas field

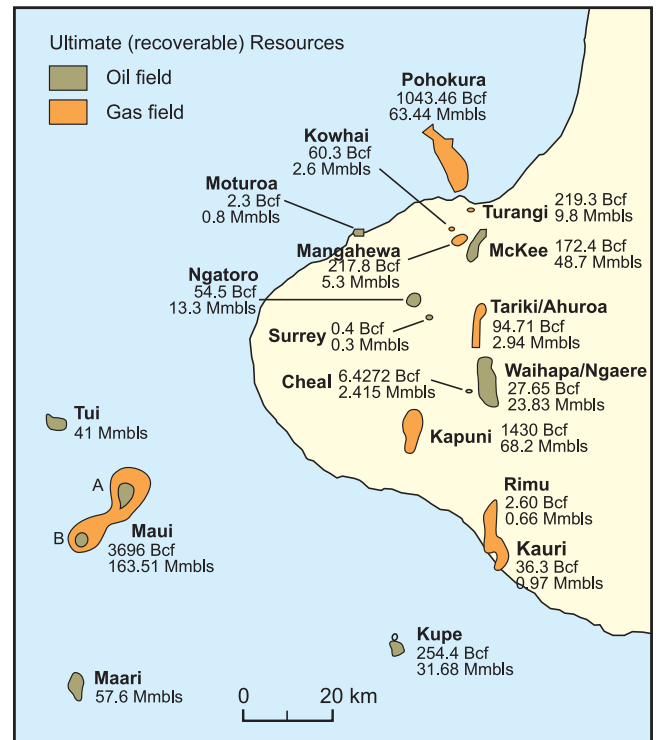


FIGURE 41 Oil and gas fields in Taranaki. Reserves statistics as at 1 January 2012. Bcf = billion cubic feet, Mmbbls = million barrels. Source: Ministry of Business, Innovation and Employment.

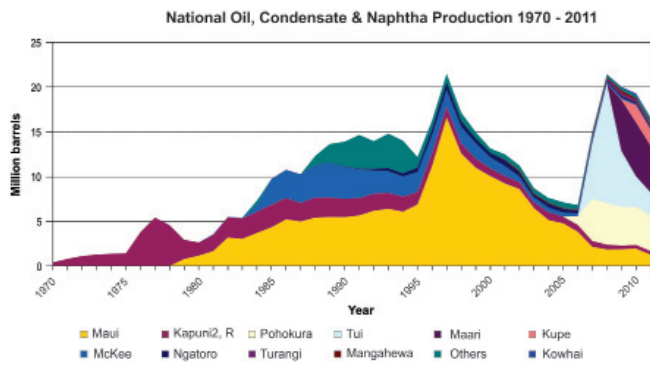


FIGURE 39 New Zealand total oil, condensate and naphtha production 1970–2011. Source: NZ Petroleum & Minerals.

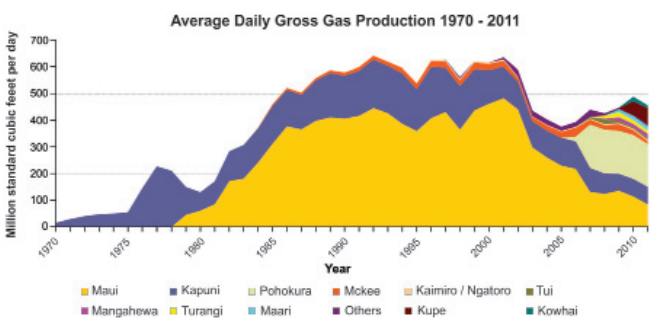


FIGURE 40 Average daily gross gas production 1970–2011. Source: NZ Petroleum & Minerals.

in the 1950s, which was the first to be developed. Since then, New Zealand’s petroleum exploration and development activities have been concentrated in the Taranaki Basin both onshore and offshore. The Taranaki Basin accounts for 547 (nearly 80%) of the 698 exploration and development wells drilled in New Zealand between 1982 and 2011. New Zealand’s petroleum exploration potential is located mainly within the offshore sedimentary basins.

Offshore petroleum — Taranaki is the only current area of oil production in New Zealand and by global standards even it is lightly explored. Offshore New Zealand has about 20 other sedimentary basins (Figure 3) that may hold recoverable oil and gas. These cover an area of about 550 000 square kilometres and may be capable of generating as much as 24 trillion barrels of oil (Uruski and Bailie 2001). The development of the small Tui field (see above) has had a significant economic impact, indicating the potential value of a major discovery.

With the much broader mandate that the 2008 United Nations Law of the Sea (UNCLOS) jurisdiction now provides, offshore exploration efforts are planned, particularly for the unexplored areas such as deep-water Taranaki, Northland, Reinga, Pegasus and Great South basins (Campbell et al. 2012). The largest structure recognised to date is the Romney prospect, with a closure area of 200 square kilometres in 1600 metres water depth and a potential to contain up to 1100–1650 million barrels of oil-in-place or between 1.57 and 2.7 million cubic feet of gas (Uruski et al. 2010). Other basins of note include the Pegasus Basin south-east of the North Island, which is largely undeformed, and the Great South Basin south-east of the South Island. The New Zealand region of Zealandia has producing petroleum basins both onshore and offshore, but with such a vast and unexplored continental area lying further out to sea, there is potential to discover continental-scale resources.

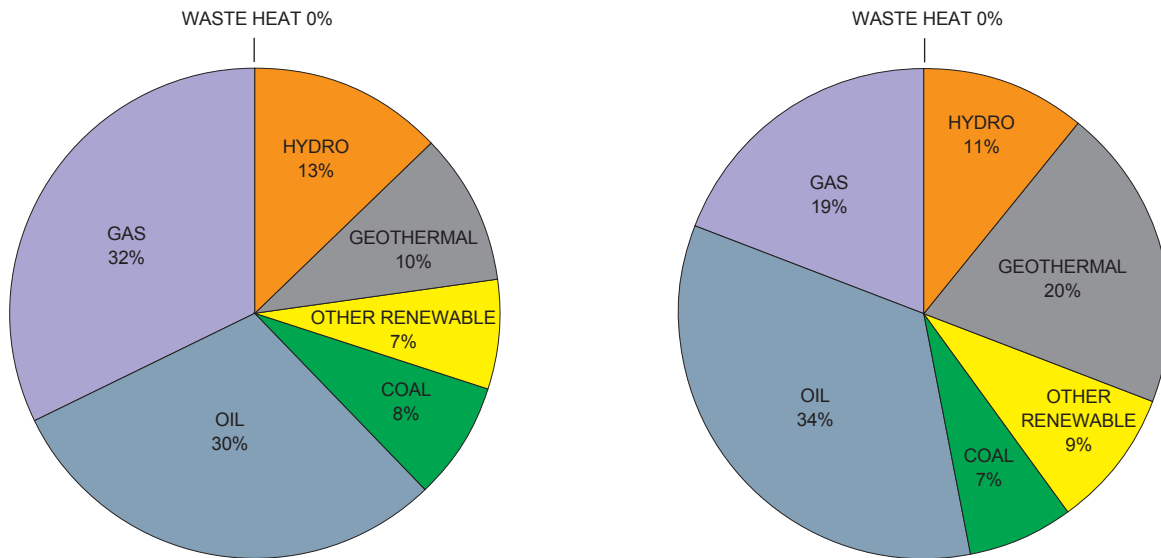


FIGURE 42 New Zealand's primary energy supply 1991 and 2011. Source: Energy Data File, 2012 'Other renewable' is wind, bioenergy and solar.

Offshore minerals

In 2008 UNCLOS accepted New Zealand's legal claim for the jurisdiction over a greatly enlarged area of sea floor, encompassing most of submarine continental Zealandia. New Zealand's Exclusive Economic Zone (EEZ) and Extended Continental Shelf (ECS) cover an offshore area of about 5.7 million square kilometres, which is about 20 times larger than the onshore area of New Zealand.

The offshore area is largely unexplored (Wood and Wright 2008) but has potential for oil (Figure 3) and gas, gas hydrates, seabed nodules and crusts containing phosphate, and metals, hydrothermal minerals (copper, zinc, gold and silver) and placer deposits of gold and ironsand (Figure 2). Parts of the area are being actively explored for petroleum and minerals (particularly phosphate).

Gold — Gold deposits in marine sediments have been recognised off the coast of onshore goldfields near Coromandel and Thames in the North Island where a combination of natural erosion and 19th and 20th century mine tailings have produced near-shore placer deposits. These have been investigated in the past, but not developed.

In the South Island, gold-bearing sediments in beach deposits have been worked along the West Coast and south coast on a small scale. West Coast offshore deposits were investigated in some detail in the 1980s, along with areas off the south coast of the South Island and offshore from the Clutha River in Otago using geophysical surveys and dredge sampling. The West Coast gave the most promising results, with a low grade resource of about 400 000 ounces being defined (Youngson and Fraser 2005). More recent investigations of the West Coast offshore deposits, with a programme of geological studies, geophysical surveys and drilling, was abandoned in mid-2011, apparently due to uneconomic results.

Ironsand — Offshore reconnaissance sampling by the New Zealand Oceanographic Institute in the 1960s and 1970s identified areas with the highest concentrations of titanomagnetite as offshore from the Waikato River to the north of Manukau Harbour, from New Plymouth to north of the Mokau River mouth, and at Patea. Aeromagnetic survey data suggest that the ironsand is concentrated in 'ribbons' representing paleo-beach and dune systems and paleo-river channels formed at times of lower sea

level (Figure 43). The 9000-year-old shoreline about 20 km off the present-day coast is recognised as a particularly important event for ironsand deposit formation. Trans-Tasman Resources has reported a resource of 482 million tonnes of concentrate (48% Fe), including 156 million tonnes indicated and 325 million tonnes inferred, in deposits offshore from Patea.

Phosphorite — Extensive phosphorite resources are present in submarine deposits along 400 km of the crest of the Chatham Rise, in water depths of about 400 metres, 670 km east of the

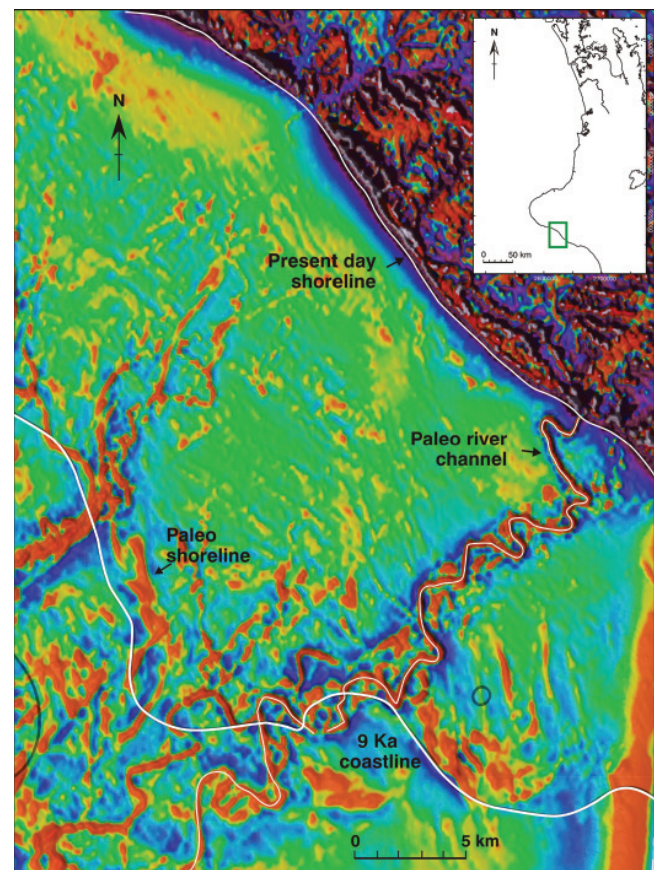


FIGURE 43 Offshore ironsands, Taranaki. Aeromagnetic survey of the Patea offshore area by World Geoscience Corporation in 1996 shows positive magnetic anomalies (red and orange) that are interpreted to represent concentrations of ironsands.

South Island. They consist of nodules, typically 10–40 millimetres in diameter, in a layer up to 70 centimetres thick, within a glauconitic sandy mud matrix. The areal distribution of the nodules is very patchy, the highest concentration averaging 66 kilograms per square metre. Dredge sampling has outlined an estimated provisional resource of 100 million tonnes of nodules averaging 21% P_2O_5 . Test trials have demonstrated that the material is suitable for use as a direct-application, slow-release phosphate fertiliser.

Volcanogenic massive sulphide deposits: New Zealand is located on a convergent plate boundary that extends off the North Island towards Tonga, and beyond. About 1200 km of the Tonga–Kermadec Arc lies within New Zealand’s EEZ. Over the last 20 years, investigations of this area have identified numerous submarine volcanoes, many of which are active. Mineralisation rich in copper, gold, lead zinc and barium has been discovered, with potentially economic grades.

Ferromanganese nodules — Iron, manganese and other minerals form by direct precipitation from seawater. Their value is in the traces of more valuable metals (cobalt, nickel and copper). There are large deposits of these nodules within New Zealand’s EEZ, the most studied of which are at abyssal depths in the deep ocean south of the Campbell Plateau. A conservative estimate of the amount of ferromanganese nodules in the New Zealand EEZ is 283 million tonnes containing about 1.5 million tonnes of nickel, cobalt and copper.

EXPLORATION FOR OUR FUTURE RESOURCES

Growth of mineral resources

Exploration for mineral resources increases with rising demand. This leads to new exploration discoveries, re-evaluation of resources and research. Figure 44 shows that since 1996, global copper production has increased by 46% to about 16 million tonnes annually, but assessed resources have grown by 120% to 690 million tonnes. The IMF metal price index, which includes the main traded metals (copper, aluminium, iron ore, tin, lead nickel, zinc and lead), has increased from 70 to 202 since 1996, spurring renewed exploration and re-evaluation of resources.

Copper has been mined for more than 5000 years, yet known copper resources may now be the largest they have ever been.

Some minerals have not followed this trend. The discovery rate for new gold resources has declined significantly since the 1990s despite a substantial increase in gold exploration spending since 2002, spurred by a five-fold increase in the gold price. Gold mine production has increased only slightly from 2590 tonnes in 2000 to an estimated 2700 tonnes in 2011 (USGS 2012), despite the five-fold price increase.

Past projections of demand and supply

Following the Second World War, concerns about the availability of resources needed for post-war reconstruction led to the US Government establishing the Paley Commission to investigate raw material supply and demand. Its report (US Government 1952) made predictions for US and global raw material demand (including oil) from 1950 until 1975. It found: ‘Consumption of almost all materials is expanding at compounding rates and is thus pressing harder against resources which, whatever else they may be doing, are not similarly expanding’. It described a ‘larger and more pervasive’ materials problem than those that had occurred in the past. The commission’s predictions of consumption growth rates proved to be conservative – global mineral production in 1975 was at least double what had been forecast

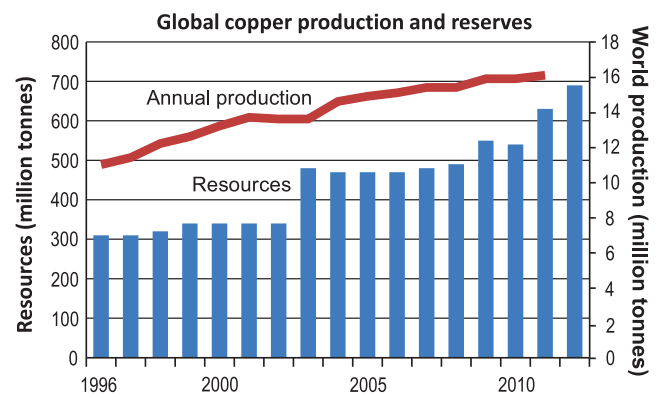


FIGURE 44 Global copper production and reserves, 1996–2012. Source: USGS (2012).

(Strauss 1986), yet resources were to grow even faster, and were much larger than they had been in 1950, despite the increased rates of consumption.

In the 1970s the ‘Limits to Growth’ study by the Club of Rome group (Meadows et al. 1972) found that if total resources were five times the size of known reserves, combined with continuing growth in consumption, petroleum resources would be exhausted in 20 years, and gold resources exhausted in just 9 years. Again, resources generally expanded faster than production and the forecasted collapse did not eventuate.

Cohen (2007) reported that a range of resources were being used up at an alarming rate including indium, a rare metal used in the production of flat video screens and other advanced electronic applications, that would be exhausted in 4 years at then current rates of consumption. Silver would be exhausted in 6 years, lead in 8 years, and copper in 38 years.

Sudden demand increases lead to rapid price increases. A 10-fold increase in the demand for indium led to the price increasing from US\$100 per kilogram in 2002 to more than US\$1,000 per kilogram in 2005–2006 but has now declined to about US\$500 per kilogram. The price increase produced a typical response. Supply has grown as a result of improved recovery of indium from zinc metal smelting, the main primary source of supply, while recycling has now increased to exceed the primary supply (USGS 2012). Indium resources have recently been estimated at 50 000 tonnes (Mikolajczak 2009) based on these improved recovery rates, which is sufficient to last for about 50 years at current rates of mine production. Price volatility and supply concerns about indium have accelerated the development of alternatives with a wide range now under investigation (USGS 2012). Price volatility is likely to continue, but, once again, fears of the exhaustion of resources have proved to be unjustified.

Renewal of mineral resources

Mineral resources are commonly described as ‘non-renewable’ as once a mineral deposit has been worked, or a coal deposit burned for energy, it cannot be used again. This is not always true for minerals, as the treated rocks (tailings) produced by mining operations always contain small quantities of potentially valuable minerals. Tailings can be treated again (sometimes more than once) as mineral treatment technology improves or prices rise. Retreatment has been widely used, particularly for gold mine tailings in South Africa and at Kalgoorlie in Western Australia.

Although individual mines have a finite life, mineral resources are not finite, and tend to expand as demand provides impetus for exploration to discover new deposits, and rising prices expand

resources at existing operations, leading to new research for alternatives and encourage conservation and recycling. The availability of resources has not been constrained by natural limits, and in more than 5000 years of mining, no raw material resources have been exhausted. Continued exploration, research and technological advances have both increased resources and allowed raw materials to be used more efficiently. Recycling has become increasingly efficient, with recycled copper now accounting for about 35% of the US copper supply, while about 65% of indium supply comes from secondary sources – recycling, manufacturing process recovery, and tailings retreatment (USGS 2012).

Global petroleum resources have grown with technological advances leading to the widespread commercial development of shale gas, an ‘unconventional’ resource, and Canadian tar sands. The International Energy Agency recently reported that the development of US oil shale resources could make it the world’s largest oil producer within 5 years (IEA, 2012), reaching a new record level of production.

Mineral exploration methods

The purpose of mineral exploration is to convert mineral potential into economic mineral resources through a process of investigation and discovery. Once a mineral commodity has been selected, exploration begins by selecting an area to investigate based on an assessment of its geological history and past mining activity. Exploration then progresses in stages, followed by decisions on whether to continue to more intensive investigations of particular areas. A successful exploration programme that begins with an area of several thousand square kilometres may lead to a detailed investigation of just a few hundred hectares that contains an economic resource. Most exploration programmes are unsuccessful, but produce useful information that may be of value to future explorers.

Reconnaissance exploration can eliminate large areas, and allow activities to be focused by defining anomalies that may be caused by economic mineralisation. Reconnaissance surveys may use geophysical sensors carried in aircraft, or on the ground, or systematically sampling of rocks, soil, stream sediments, and sometimes plants for chemical analysis (Figures 45–47). The effects of these methods on the land and landusers are generally minimal. The results are interpreted along with existing geological and past exploration data to define areas for more detailed investigation that are called ‘prospects’.

Numerous geophysical, geochemical, and geological methods have been developed to assist with the detailed investigation of prospects. The methods to be used are selected to suit the type of mineral deposit being sought. They include ground geophysical surveys, sampling of rocks, soil, and bedrock by hand, and using shallow drilling techniques together with field geological mapping, supported by mineral studies of samples in a laboratory. If successful these methods will define potential mineral deposits (targets) that can be tested by drilling.

Drill testing of prospects usually includes diamond drilling that collects continuous core samples (Figure 48). This method is the most expensive, costing several hundred dollars for each metre drilled, but it provides the most information as it produces samples of rock that are relatively undisturbed. Much cheaper drilling methods that produce crushed rock samples are often used to determine the continuity of mineral content between the diamond drill holes, reducing the cost. Drill cores are examined and described in detail, samples are analysed, and a range of scanners can determine mineral composition. All the data are recorded



FIGURE 45 Collecting a stream sediment sample for geochemical analysis. Photo: Tony Christie.



FIGURE 46 Airborne geophysical survey of the Taupo Volcanic Zone in 2005. The magnetometer sensor is mounted in a ‘stinger’ at the rear of the aeroplane. Photo: Glass Earth Gold Ltd.



FIGURE 47 Ground magnetic survey, Central Otago. Photo: Glass Earth Gold Ltd.

in a three-dimensional digital database.

Once a potentially economic mineral deposit has been discovered, detailed drilling to prove up resources is followed by investigation of mining feasibility. This will include mining methods, as well as metallurgy (the processing needed to extract minerals from the mined rock) and project economics as well as environmental, social, and government-related issues.

The time required from commencing reconnaissance exploration to developing an operating mine is commonly about 10 years, and may be longer for large, complex projects.

Mineral exploration trends

Mineral resources are natural resources that are created by natural geological processes. They can be seen as providing subsurface ecological services. They differ from other resources in being concealed. To maintain output, continuing exploration investment is needed to discover and define new resources. The global mineral exploration industry is comparatively small, consisting of specialist exploration companies and exploration divisions of major private and public sector mining companies. Total spending on exploration for minerals other than iron and uranium over the last decade has ranged from less than US\$3 billion in 2002 to an estimated US\$18 billion in 2011 (Figure 49). As a comparison, the sales value of McDonald's restaurants in 2011 was US\$27 billion. Exploration spending closely tracks commodity prices, which have been particularly volatile since 2007.

In New Zealand most exploration investment is sourced from overseas; the exploration investment sector in New Zealand is very small, consistent with a long-standing lack of interest by New Zealand investors in investing in New Zealand's industry.

NZP&M collects information from exploration and prospecting permit holders. Prospecting includes surveys carried out over large areas to locate areas of interest for more detailed evaluation under exploration permits. NZP&M data show that exploration spending for coal and other minerals (mainly gold), both onshore and offshore and including non-exploration costs such as access and consents, has increased from NZ\$2.5 million in 2000 to NZ\$37 million in 2011 (Figure 50). However, non-exploration costs have been rising, accounting for nearly 40% of exploration spending in recent years. Since 2005 exploration investment in New Zealand has been static (see Figure 50) while global exploration investment has increased strongly. New Zealand's share of exploration investment is declining and at present levels is inadequate to make the most of New Zealand's mineral potential. No new mineral deposits away from known resources close to existing producers have been discovered and developed for more than 20 years.

Despite the comparatively low level of exploration investment, New Zealand's gold resources have expanded as a result of near-mine exploration at the three operating gold mines (at Waihi in the North Island, and at Reefton on the West Coast and Macraes in Otago) where significant resource discoveries continue to be made. While this has allowed output to be maintained, overall the industry is neither growing, diversifying nor realising its potential economic contribution.

Exploration is financially risky; an industry rule of thumb is that for every 1000 prospects that are identified, 100 are investigated in some detail, 10 are tested with substantial drilling programmes, and 1 new mine results (Figure 51). The main product of exploration is information, and reporting systems have been developed to manage this, allowing data from unsuccessful



FIGURE 48 Drilling. Photo: OceanaGold Ltd.

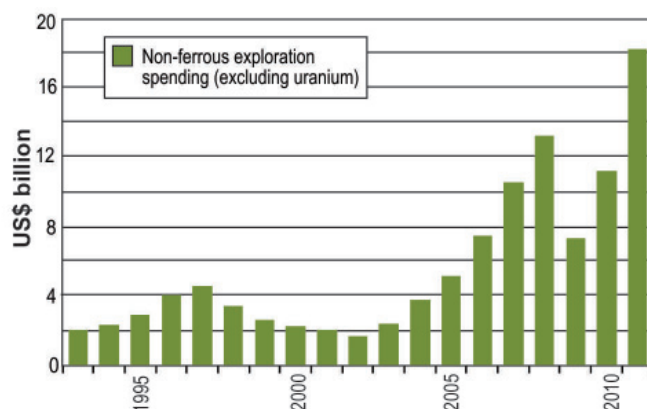


FIGURE 49 Estimated non-ferrous exploration budget totals 1993–2011. Source: Metals Economics Group.

exploration programmes (which are the majority) to be added to published databases for minerals, petroleum and coal.

In most countries rich in mineral resources, minerals in their natural state are owned by the public. Exclusive rights to explore and mine are granted to companies by government agencies for fixed terms. In New Zealand all gold, silver, uranium and petroleum is owned by the Crown (i.e. the public), and other minerals and coal on private land may be owned by the Crown, the land owner or some other person. Permits to explore and mine Crown-owned minerals, coal, and petroleum are granted by NZP&M. The ownership of other minerals and coal is complex and fragmented and no consistent, reliable database of their ownership is readily available.

While exploration for Crown-owned minerals is in progress, the exploration information produced is reported to the government and held confidential until the company relinquishes its interests or a time period has elapsed (5 years in New Zealand) when the data become 'open file' and are available to other explorers. The industry is very unusual in having its national information database managed by the government. In New Zealand the database contains several thousand reports and an increasing

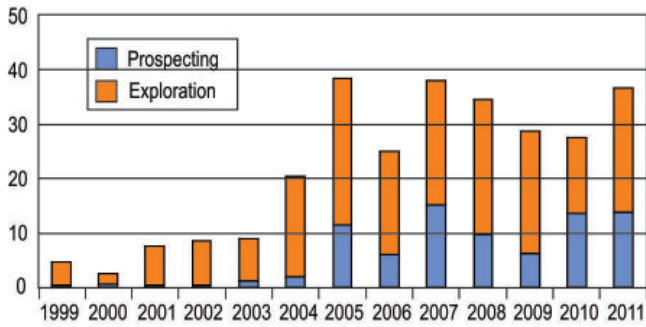


FIGURE 50 Exploration spending for minerals and coal 1999–2011. Source: NZ Petroleum & Minerals.

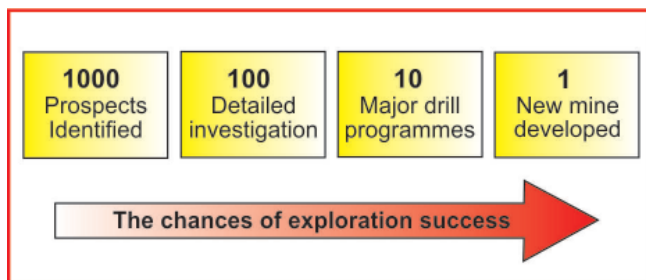


FIGURE 51 Exploration risk.

amount of digital data on petroleum, minerals, and coal investigations with a replacement value of more than NZ\$1 billion that has been acquired at relatively modest public cost. It is managed by NZP&M.

The annual budget for government-funded mineral research in New Zealand is about NZ\$5 million, covering metallic and non-metallic minerals both onshore and offshore as well as related environmental research. The level of mineral research spending is very low when compared with the total value of New Zealand's resource potential, which is estimated at about NZ\$200 billion just for onshore mineral resources. Research can add value to the resource database. It can improve our understanding of New Zealand's mineral deposits and help develop and refine exploration techniques applicable to this country, and attract new exploration investment.

In 2011, the government (via NZP&M) completed an airborne geophysical survey of the Northland Region and another is in progress on the West Coast of the South Island, primarily to support mineral exploration by the private sector. Since 2005, offshore seismic surveys to support petroleum exploration have been carried out by the government over five sedimentary basins (Campbell et al. 2012).

Petroleum exploration

Exploration for oil and gas generally follows a similar process to exploration for minerals, but the target may be deeply buried. Therefore reconnaissance exploration generally consists of seismic surveys to obtain images of the sedimentary sequences at depth and to identify potential reservoir rocks and traps. Drilling costs for oil and gas are in the order of several millions of dollars per well, 10–100 times that of other mineral exploration drilling. Even if the well strikes oil or gas, there is the added requirement that the reservoir rock must have sufficient permeability for wells to produce at an economic rate.

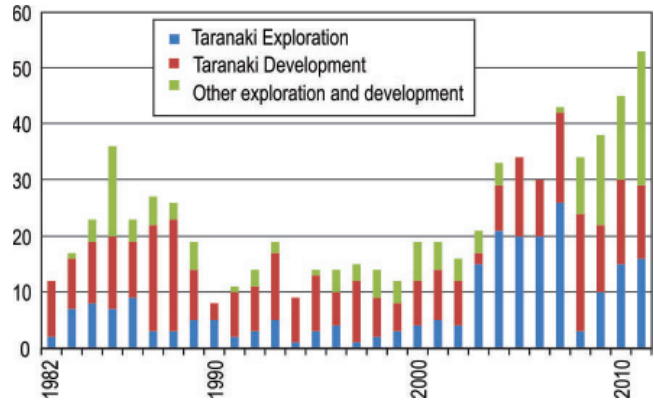


FIGURE 52 Petroleum exploration and production wells, 1982–2011. Source: NZ Petroleum & Minerals.

Petroleum exploration trends

Figure 52 shows the number of petroleum exploration wells drilled between 1999 and 2011. Because of the high cost of offshore drilling, most of the wells have been drilled onshore. Most of this exploration has been focused on the Taranaki Region, although 17 other petroleum basins could contain commercial deposits. Limited exploration of other basins has occurred, and sub-commercial discoveries have been made in the East Coast Basin, Canterbury Basin, and Great South Basin. The significance of these discoveries proves the presence of effective petroleum systems outside of Taranaki, and provides encouragement for future exploration. Studies by GNS Science (Funnell et al. 2009; King et al. 2009) estimated that there is a 90% chance that resources totalling 1.9 billion barrels of oil remain in the eight sedimentary basins modelled and a 50% chance there are 6.5 billion barrels. Most of these estimated undiscovered resources are in the offshore parts of the Taranaki Basin and in the Great South Basin.

Exploration is needed to convert this potential into economic resources, but the success rate for exploratory wells is low. In offshore Taranaki, of the 82 exploration wells drilled, 5 have made commercial discoveries. Only 27 wells have been drilled into the remaining offshore basins and many remain to be tested by drilling (Bush 2012).

FURTHER INFORMATION

The book *Mineral Wealth of New Zealand* (Thompson et al. 1995) provides a general introduction to minerals, coal and petroleum in New Zealand, whereas more detail is given in reports by MacFarlan and Barry (1991; minerals), Geosearch (1991; petroleum) and Barry et al. (1994; coal). Technical descriptions of New Zealand's mineral deposits can be found in a series of AusIMM monographs by Williams (1974), Kear (1989) and Christie and Brathwaite (2006), and the 1:1 million scale metallogenic map of Brathwaite and Pirajno (1993). Minerals and petroleum databases are accessible from the GNS Science website (www.gns.cri.nz), and the New Zealand Petroleum & Minerals website (www.nzpam.govt.nz) has summary information, production statistics and permit databases. Key publications available from www.nzpam.govt.nz are a series of mineral commodity reports originally published in New Zealand mining (e.g. Christie et al. 2001), a series of Fact Sheets and the publication *New Zealand Petroleum Basins*, an overview of the oil and gas industry in New Zealand that provides a detailed breakdown by basin of prospectivity, drilling history, plays, reservoirs and production.

ACKNOWLEDGEMENTS

Carolyn Hume drafted most of the figures. Bob Brathwaite, Hamish Campbell and David Skinner reviewed the manuscript. Funding was provided by Science and Innovation, Ministry of Business, Innovation and Employment.

REFERENCES

- Barry JM, Duff SW, MacFarlan DAB 1994. Coal resources of New Zealand. Energy and Resources Division, Ministry of Commerce, Resource Information Report 16.
- Brathwaite RL, Pirajno F 1993. Metallogenic map of New Zealand. Institute of Geological and Nuclear Sciences Monograph 3. 215p.
- Bush C 2012. Our petroleum future. PEPANZ chairman's address to the NZ Petroleum summit. 19 September 2012, Wellington, Petroleum Exploration and Production Association of NZ.
- Campbell H, Malahoff A, Browne G, Graham I, Sutherland R 2012. New Zealand geology. Episodes Vol 35 no 1. IUGS March 2012.
- Christie AB, Brathwaite RL 1999. The mineral potential of New Zealand. Institute of Geological and Nuclear Sciences, Science Report 1999/4.
- Christie AB, Brathwaite RL eds 2006. Geology and exploration of New Zealand mineral deposits. Australasian Institute of Mining and Metallurgy Monograph 25. 353 p.
- Christie AB, Thompson BN, Brathwaite RL 2001. Mineral commodity report 22 – aggregate. New Zealand Mining 30: 6–26.
- Christie AB, Heron DW, Graham IJ, Davy BW 2009. Genetic model for exploration of offshore West Coast Ironsands, North Island, New Zealand. In: Williams PJ et al. eds Smart science for exploration and mining, Proceedings of the 10th Biennial SGA meeting of the Society for Geology Applied to Mineral Deposits, Townsville. Pp. 979–981.
- Cohen D 2007. Earth's natural wealth: an audit. New Scientist issue No. 2605, 23 May 2007.
- Funnell R, King P, Stagpoole V, Uruski C, Field B, Isaac M 2009. Potential undiscovered oil and gas resources of New Zealand, Phase II. GNS Science Letter report 2009/101LR (available from www.med.govt.nz/sectors-industries/natural-resources/oil-and-gas/petroleum-expert-reports/GNS-science-report-pdf/view)
- Geosearch 1991. Petroleum resources of New Zealand. Energy and Resources Division, Ministry of Commerce, Resource Information Report 10.
- JORC 2012. Joint Ore Reserves Committee, Australasian code for reporting mineral exploration results, mineral resources and ore reserves (available from www.jorc.org).
- Hector J 1869. On mining in New Zealand. Transactions of the NZ Institute 2: 364–386.
- IEA 2012. A renaissance in US production – light tight oil. Feature topic, Journal of the International Energy Agency, Issue 3 Autumn 2012.
- Kear D ed. 1989. Mineral deposits of New Zealand. Australasian Institute of Mining and Metallurgy Monograph 13. 225 p.
- King P, Funnell R, Stagpoole V, Uruski C, Field B, Henrys S 2009. Potential undiscovered oil and gas resources of New Zealand. GNS Science Letter report 2009/34LR (available from www.med.govt.nz/sectors-industries/natural-resources/oil-and-gas/petroleum-expert-reports/GNS-science-report-pdf/view)
- MacFarlan DAB, Barry JM 1991. Mineral resources of New Zealand. Energy and Resources Division, Ministry of Commerce, Resource Information, Report 11.
- Meadows DH, Randers J, Behrens W 1972. Limits to growth. Potomac Associates.
- Mikolajczak C 2009. Availability of indium and gallium. Available at <http://documents.indium.com/qdynamo/download.php?docid=552>
- Strauss SD 1986. Trouble in the third kingdom. Mining Journal Books Ltd, 1986.
- Thompson BN, Brathwaite RL, Christie AB 1995. Mineral wealth of New Zealand. Institute of Geological and Nuclear Sciences Information Series 33. 170 p.
- Torckler LK, McKay D, Hobbins J 2006. Geology and exploration of the Favona Au-Ag deposit, Waihi, Hauraki Goldfield. Australasian Institute of Mining and Metallurgy Monograph 25: 179–184.
- Uruski C, Baille P 2001. Petroleum potential of New Zealand's deep water basins. In: Hill KC Bernecker T eds Eastern Australasian Basins Symposium, 25–28 November 2001, Melbourne, Victoria. Australasian Institute of Mining and Metallurgy Special Publication / Petroleum Exploration Society of Australia. Pp. 151–158.
- Uruski C, Reid E, Stagpoole V, Herzer R, Griffin A, Bland K, Ilg B, Browne G 2010. The Reinga Basin, North Island New Zealand. APPEA Journal 50: 287–308.
- US Government 1952. Resources for freedom. The President's materials policy commission report, 1952. Chairman WS Paley.
- USGS 2012. US Geological Survey mineral commodity summaries, 2012. 198 p. <http://minerals.usgs.gov/minerals/pubs/mcs/2012/mcs2012.pdf>
- Walton M, Barker RG, Christie AB 2002. Quantifying the opportunity cost of New Zealand's mineral potential. Proceedings of the AusIMM 2002 annual conference, Australasian Institute of Mining and Metallurgy Publication Series 6/02: 143–148.
- Williams GJ 1974. Economic geology of New Zealand. 2nd edn. Australasian Institute of Mining and Metallurgy Monograph Series 4.
- Wood R, Wright I 2008. NZ's offshore mineral resources – opportunities and challenges. Proceedings of the Australasian Institute of Mining and Metallurgy NZ Branch 2008 annual conference. Pp. 617–624.
- Youngson and Fraser 2005. Seafield Resources' offshore alluvial gold project, Westland, New Zealand. Proceedings of the New Zealand Minerals Conference, Crown Minerals and AusIMM NZ Branch, Auckland, November 2005.