Mineral Commodity Report 12 — Tungsten

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Symbol	W
Atomic no.	74
Atomic wt	183.85
Specific gravity	19.3
Valence	6, 5, 4, 3, 2
Melting point	3410˚C
Boiling point	5930˚C
Crustal abundance	1.2 ppm
Preferred analysis method	x-ray fluoresence spectroscopy
Routine detection limit	10 ppm

Discovery and Origin of Names

Tungsten was first isolated from the mineral wolframite in 1783 by the Spanish d'Elhuyar brothers, Juan Jose and Fausto, although its existence had been suggested by the earlier (1781) experiments of the Swedish chemists Torbern Bergman and Carl Wilhelm Scheele. Tungsten came into general use in steel alloys following the discovery in 1898 that steel containing tungsten could be used to cut other steels.

The name tungsten, from the Swedish *tung* heavy, and *sten* stone, was first used about 1758 for the mineral now called scheelite. An alternative name is wolfram (German) from *wolframite*, derived from *wolf rahm* because wolframite interfered with the smelting of tin and was supposed to devour the tin. The name of the tungsten ore mineral scheelite is after C.W. Scheele.

Major Ores and Minerals

Tungsten is never found free in nature, but occurs in combination with other metals, notably as tungstate minerals of the scheelite series (solid solution mixture of scheelite $CaWO_4$ and powellite $CaMoO_4$ and wolframite series (solid solution mixture of ferberite $FeWO_4$ and huebnerite $MnWO_4$), which are the important tungsten ores. These minerals form primary ores with a variety of coproducts or may themselves be obtained as coproducts.

Properties

Tungsten is one of the transition elements in Group VIB of the periodic table. Pure tungsten has a lustrous silver-white to grey appearance and is ductile. Tungsten has the highest melting point, lowest vapour pressure, highest tensile strength at elevated temperature (>1650˚C), and the lowest coefficient of thermal expansion of all the metals. It has good thermal and electrical conductivity, and excellent corrosion resistance, although it oxidises in air at elevated temperatures.

Scheelite is white, yellow, green or brown in colour, translucent with an adamantine lustre, and has a hardness of 4.5 to 5, and a specific gravity of 5.9 to 6.1. It has tetragonal crystal symmetry with crystals forming simple dipyramids, although a more typical form is as granular aggregates. Scheelite emits a bright, bluish-white fluorescence under ultraviolet light, a property utilised in identification and exploration for the mineral by "lamping" of panned concentrates, veins and bedrock. Increasing molybdenum content changes the colour from blue to pale yellow, and orange.

Wolframite is brown to black in colour, opaque with a submetallic lustre, has a hardness of 5 to 5.5 and a specific gravity of 7.0 to 7.5. It is monoclinic, forming bladed crystals, usually flattened parallel to the front side pinacoid, or massive granular aggregates.

Formation

Tungsten minerals are predominantly found in deposits formed by hydrothermal fluids associated with igneous intrusions of granitic composition, and less commonly with regional metamorphism, or in placers resulting from the erosion of these and other types of deposits. Most primary tungsten production is from skarns and wolframite-bearing quartz veins. A significant quantity has also been produced as a coproduct of mining porphyry molybdenum deposits. Much less important are greisen, pegmatite/aplite, mesothermal quartz vein, and stratiform/stratabound deposits.

Skarn deposits

Skarns are calc-silicate rocks, containing Ca-Mg minerals such as pyroxenes, garnets and wollastonite, that are formed by metasomatic replacement of carbonate rocks along contacts with granitoid intrusions. Tungsten skarns contain scheelite accompanied by molybdenite, chalcopyrite, pyrrhotite, pyrite and magnetite. The deposits are typically small, averaging about 1.1 Mt and grading 0.7% WO_3, with most lying in the range of 0.05 to 22 Mt and grading from 0.34 to 1.4% WO_3. Shizhuyuan in southeastern Hunan province, China and MacMillan Pass on the Yukon-North West Territories border in Canada are of a similar size and are the largest known tungsten deposits in the world. MacMillan Pass has resources of 63 Mt grading 0.95% WO_3. Other examples are: King Island in Australia; Cantung in North West Territories and Mactung in Yukon Territory, Canada; Pine Creek and Strawberry in California, USA; Uludag, Inlufer and Telekai in Turkey; Sangdong in South Korea; Salau in Ariége, France; and Tyrny Auz (North Caucasus), Lyangar, Chorukh-Dairon and Maykhura in the Commonwealth of Independent States (CIS). Most of these deposits are associated with calc-alkaline granitoid intrusives of mid-Paleozoic to late Cretaceous ages.

Greisen deposits

Tungsten minerals, usually accompanied by cassiterite, occur in lodes, stockwork veins, disseminated in massive greisenised granite, and in quartz-sulphide veins, within or near the apical parts (cupolas) of highly fractionated biotite or biotite-muscovite granites. The greisen is formed by post-magmatic metasomatic fluids and consists of a granoblastic aggregate of quartz and muscovite (or lepidolite) with accessory topaz, tourmaline and fluorite. Tungsten is usually present as wolframite, but some deposits contain scheelite. Examples are Akchatau, Kara-Oba and Iultin in the CIS; Erzgebirge on both sides of the Czech-German border (e.g. Cinovec, Czech Republic; and Sadisdorf, Germany); Panasqueira in Portugal; Lost River in Alaska; Wolfram Camp in Australia; Xihuashan in China; Mawchi in Myanmar; and Yugodzyr in Mongolia.

Granite related, wolframite-quartz and scheelite-wolframite-quartz veins

Wolframite, molybdenite and minor base-metal sulphides occur in quartz veins associated with multiphase biotite or biotite-muscovite granite stocks which have intruded sandstone, shale and their metamorphosed equivalents. These deposits are associated with highly fractionated leucocratic granites which range in age from Paleozoic to late Tertiary. Hydrothermal alteration zones include albitisation, K-feldspar (+REE), greisenisation and chloritisation. The deposits range in size from 0.045 to 8.0 Mt and average 0.56 Mt, with grades ranging from 0.5 to 1.4% WO_3 and averaging 0.9% WO_3. The main deposits occur in southeastern China, including the largest, Xihuashan in the Daya district, Jiangxi Province. Other examples are Dajishan in Jiangxi province, China; Panasqueira in Portugal; Los Avestruces in Argentina; Chicote Grande in Bolivia; Pasto Bueno in Peru; Bi'r Tawila in Saudi Arabia; and Story's Creek in Tasmania.

Of much smaller size are scheelite-wolframite-quartz vein deposits related to less fractionated monzonite or granodiorite intrusions (Hutchison, 1983). In these deposits scheelite is more abundant than wolframite, and associated minerals are cassiterite, pyrite, molybdenite, arsenopyrite and base-metal sulphides. They occur in Southeast Asia (e.g. southern Jiangxi Province, China), and the scheelite occurrences associated with granites in western South Island appear to belong to this subtype.

Porphyry deposits

Porphyry molybdenum deposits: Tungsten has been produced as a coproduct (usually along with tin) from Climax-type porphyry molybdenum deposits. These deposits are associated with multiple intrusions of A-type, peralkaline granites, rhyolites and quartz-rich porphyries. Molybdenite, accompanied by fluorite and pyrite, is mainly in stockwork quartz veinlets associated with intense silicification. Tungsten occurs as huebnerite and wolframite. Examples include: Climax and Urad-Henderson in Colorado, Questa in New Mexico and Pine Grove in Utah.

Porphyry tungsten-molybdenum deposits: Scheelite and/or wolframite and molybdenite occur as disseminated grains, in veins and veinlets, and in breccia pipes in or above epizonal granitic rocks. The deposits are associated with the late phases of subvolcanic rhyolite porphyry and microgranite, or deeper granodiorite to granite (monzogranite) stocks, emplaced into clastic sedimentary rocks. Hydrothermal alteration zones are not as well developed as in Climax type deposits. Porphyry W-Mo deposits are typically medium to large, low grade deposits grading 0.1–0.4% WO_3 and 0.01–0.2% Mo. For example, Mount Pleasant in New Brunswick, Canada contained a resource of 9.4 Mt grading 0.39% WO_3 and 0.2% MoS_2, and Logtung in Yukon, Canada had 162 Mt at 0.13% WO_3 and 0.052% MoS_2. Other examples are Yangchuling in Jiangxi province and Xingluokeng in Fujian province, China.

Pegmatite/aplite deposits

Wolframite occurs in some quartz-microcline pegmatites and aplites, and is produced as a co-product along with columbite, tantalite, beryl, spodumene and cassiterite. The main deposits are Precambrian in age and include: Kular and Priskatel in the CIS; Bikita in Zimbabwe; Manono-Kitotolo in Nigeria; and Wodgina in Western Australia. Tungsten production from this type of deposit is relatively minor but some deposits are an important source for placer deposits.

Mesothermal scheelite-bearing quartz veins

Quartz is the dominant mineral and is accompanied by scheelite, with minor amounts of gold and sulphides, such as pyrite, arsenopyrite and stibnite. Tungsten is commonly recovered as a coproduct of gold mining. The mineralisation occurs in greenstone belts in the deposits of Archean age and in metagreywacke-slate belts of Paleozoic and Mesozoic age. Hydrothermal alteration assemblages are characterised by sericite, carbonate and chlorite. Examples of Archean age are Hollinger and MacIntyre in Canada, and Higginsville in Western Australia; Mesozoic examples are Glenorchy and Wakamarina in New Zealand.

Stratiform/stratabound deposits

Stratiform scheelite in mafic metavolcanics: Stratiform scheelite mineralisation, commonly with stibnite and cinnabar in some metavolcanic sequences, was considered to be volcanogenic exhalative in origin by Höll and Maucher (1976). A possible modern analogue is Frying Pan Lake at Waimangu Geothermal Field (Seward and Sheppard, 1986). Examples occur in Austria (Kleinarltal and Mitersill), Sardinia, Turkey, Spain, Argentina, Broken Hill district Australia, and New Mexico USA. Of these only the Mitersill Deposit has been mined at up to 400,000 t/y grading 0.5% WO_3 in 1980. Detailed isotopic and geochemical studies of the Mitersill deposit have shown that the tungsten was concentrated from mafic boninitic volcanics into a system of quartz veins during two high-grade metamorphic events (Thalhammer et al., 1989). Some tungsten skarn deposits have also been proposed as stratiform deposits, eg Sangdong in South Korea.

Stratabound tungsten-manganese oxide-quartzite: Tungsten is contained in manganese minerals (pyrolusite, psilomelane, cryptomelane, hollandite and wad) and less commonly in iron oxides and hydroxides that occur as disseminations, veins and pods within sequences of carbonate, siliceous and volcanogenic sediments. These deposits are believed to have been formed by subaqueous, epithermal hot springs. Examples are Golconda in Nevada; Talamantes in Mexico; and Romanéche in France.

Tungsten-bearing brines and evaporites: These deposits occur in recent lakes or the saline deposits of paleolakes in areas of arid climate. At Searles Lake, California, tungsten is present in evaporites covering an area of about 40 km^2 and up to 50 m thick. The deposits contain 0.005–0.008% WO_3, with reserves estimated at 170,000 t. The tungsten originated from the leaching of tungsten deposits in the upper drainage basin.

Placers

Placer deposits, formed by the erosion of the previous types of deposits, have had relatively minor production of tungsten. Examples are in China and Atolia in California.

Uses

Tungsten is used mainly in the manufacture of cutting and wear resistant materials such as tungsten carbide and steel alloys. More than half of the tungsten production is used in tungsten carbide (WC), which is noted for its hardness (9.5 on Mohs scale). Tungsten carbide is used alone or with other metals for cutting tools, mining and drilling tools, dies, gauges, bearings and the cutting edge of saws and drills. Stellites (Co-Cr-W alloys) are used for metal-cutting tools and as hard-facing materials for items such as valves, bearings, rock crushers and marine propeller shafts. Tungsten steels are used for high-speed cutting tools, dies, pneumatic tools, punches, bushings and taps, and some have also been used in the aerospace industry to fabricate rocket nozzle throats and leading-edge reentry surfaces.

Unalloyed tungsten, in the form of wire, is used as filaments for electric lamps, in electron and television tubes, and as heating elements for electrical furnaces and heaters. Tungsten rods are used as lamp filament supports, electrical contacts and electrodes for arc lamps.

Tungsten compounds have a number of industrial applications. Calcium and magnesium tungstates are widely used as phosphors in fluorescent lighting and television tubes. Sodium tungstate is used in the fireproofing of fabrics and in the preparation of tungsten-containing dyes and pigments used in paints and printing inks. Other salts of tungsten are used in the chemical and tanning industries. Tungsten disulphide and tungsten diselenide are used as dry, high-temperature (stable to 500˚C), lubricants.

Price

Tungsten prices fell steadily for about 10 years before an increase in demand in late 1993 was coupled with higher prices. This increase was fuelled in 1994 by changes in the tax system in China and also by the reduction of stocks in China following the closure of several uneconomic mines (Maby, 1995). Prices of tungsten, quoted in metric tonne units (1 mtu contains 10 kg WO_3), were around US$60 per tonne unit (US$4,758 per tonne of tungsten metal) in March 1996.

World Production and Consumption

The annual world supply of tungsten is about 42,000 t W, made up mostly of mine production, supplemented by draw-off from stockpiles and a limited amount of recycled scrap. World supply is dominated by China (32,250 t W in 1994), with lesser quantities from the CIS (8,490 t), Bolivia (540 t), Peru (330 t), North Korea (200 t), Austria (no supply recorded in 1994 but 200 t in 1993), Portugal (150 t), Thailand (125 t), Myanmar (115 t), Brazil (90 t), Australia (75 t), Rwanda/Uganda (65 t), Mexico (60 t) and South Korea (55 t) (Maby 1995). There is significant resource potential in these countries and also in Burma, Canada, Malaysia, Turkey and USA. Reliable world production is dominated by about 25 mines. Numerous small mines are active only during periods of high prices and price support.

Tungsten consumption is related to its use in industry and the state of the world economy. In 1994, world consumption matched world supply, estimated at 42,135 t of tungsten.

Ore Processing, Smelting and Refining

Tungsten ores, typically with less than 1% WO_3, are crushed and ground to liberation size, and concentrated to 65% or more WO_3 by various separation steps (flotation, gravity, magnetic) and purification by acid leaching.

The production of tungsten metal from the concentrates consists of the conversion of tungsten minerals to an intermediate compound that can be readily purified and then reduced. Firstly, scheelite and wolframite are converted to tungstic acid H_2WO_4. Scheelite concentrates are treated with hot, concentrated hydrochloric acid, resulting in precipitation of tungstic acid. Wolframite concentrates are fused with sodium carbonate to yield sodium tungstate Na_2WO_4. The soluble sodium tungstate is then extracted with hot water and treated with hydrochloric acid to yield tungstic acid. The tungstic acid is dissolved in aqueous ammonia and evaporated to produce crystals of ammonium paratungstate. The latter compound is washed and dried to produce tungsten trioxide, which is reduced by hydrogen in an electric furnace. The resulting pure tungsten powder is reheated in molds in an atmosphere of hydrogen and pressed into bars, which are hammered and rolled at high temperature to compact them and make them ductile.

New Zealand Occurrence and Resources

The occurrence of tungsten in New Zealand has been reviewed by Officers of the New Zealand Geological Survey (1970), Williams (1974), and Brathwaite and Pirajno (1993). The most significant occurrences are in schist-hosted quartz-scheelite±gold lodes in Otago (Glenorchy, Macraes) and Marlborough (Wakamarina). Scheelite also occurs in quartz veins associated with granite in Northwest Nelson, Buller and Westland. Wolframite accompanies cassiterite in greisen on the Tin Range in southern Stewart Island. Minor wolframite accompanies molybdenite, tourmaline, pyrrhotite, chalcopyrite, sphalerite and pyrite around the margin and contact aureole of a quartz-diorite pluton at Paritu, Coromandel Peninsula (Skinner, 1976). Other tungsten minerals found in New Zealand include tungstite and huebnerite (Railton and

Watters, 1990). Barraclough and Reay (1970) reported 13 analyses of scheelite from various localities in the South Island, and noted that they were essentially molybdenum free but contained up to 0.92% SrO.

Greisen deposits

A number of hydrothermal vein and greisen type W-(Sn) occurrences have been discovered along the western side of the Karamea Batholith in southwest Nelson and Westland (Pirajno, 1985; Tulloch and Mackenzie, 1986; Brathwaite and Pirajno, 1993). In contrast to classic Sn-W granite provinces (eg northeast Tasmania), the mineralisation is unusual in having scheelite dominant over wolframite and cassiterite, together with a paucity of fluorite and topaz (Tulloch and Brathwaite, 1986). The greisen of the Tin Range on Stewart Island is more typical of the classic type, in containing cassiterite and wolframite and no scheelite (see Tin commodity report page 9–15 this volume)

Bateman Creek: Scheelite is disseminated in greisenised granite and in quartz veins hosted by greisenised granite and the adjacent Greenland Group metasediments (Pirajno and Bentley, 1985). The quartz veins form sheeted systems roughly parallel to the contacts between metasediments and greisenised granite. Minerals present include: scheelite, pyrite, hematite, chalcopyrite, bornite, covellite, marcasite, molybdenite and cassiterite. The mineralised granite consists of at least three small cupolas, 350–1000 m long and 100–400 m wide, emplaced along northnorthwest trending lineaments. The greisen alteration consists of muscovite, albite, tourmaline, topaz and fluorite.

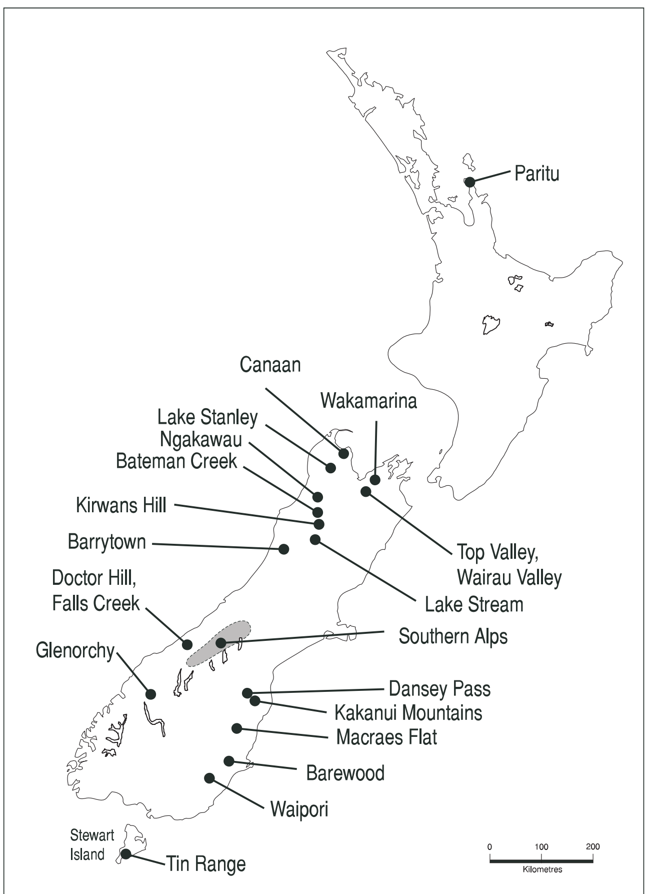

Figure 1: Location of tungsten occurrences in New Zealand.

Kirwans Hill: Scheelite mineralisation, accompanied by minor cassiterite, pyrrhotite and chalcopyrite, is present in a sheeted quartz vein system emplaced within a major northnorthwest striking fracture zone in tourmalinised Greenland Group rocks (Bentley, 1982; Pirajno and Bentley, 1985). Tungsten is present in low concentrations (0.1 to 0.75% WO_3). Bentley (1982) recognised five stages of alteration:

1. biotite-tourmaline-muscovite greisen
2. metasomatic phlogopite-clinozoisite-scheelite
3. pyrrhotite replacement of biotite, tourmaline and muscovite
4. deposition of quartz veins with W-Sn mineralisation
5. later hydrothermal activity with deposition of pyrite, calcite and sericite in crosscutting fractures

The quartz veins range from 0.01 to 0.2 m thick and contain tourmaline, apatite, orthoclase, fluorite, scheelite, pyrrhotite, chalcopyrite, pyrite, arsenopyrite, loellingite, minor sphalerite, molybdenite, cassiterite, Ag-Pb-Bi sulphosalts, and supergene covellite, bornite and tungstite. Muscovite from a quartz vein selvage at Kirwans Hill gave a K-Ar age of 296 Ma (late Carboniferous).

Barrytown: Scheelite mineralisation is associated with a small pluton of potassic S-type granite intruding Greenland Group metasedimentary rocks, which are locally hornfelsed at contacts (Mackenzie and Price, 1985; Tulloch, 1986). Disseminated scheelite is present in a series of quartz-tourmaline veins and adjacent 1–2 m wide zones of greisenised granite or greywacke. Scheelite is accompanied by minor pyrite, rutile, hematite and pyrrhotite, and rare chalcopyrite, cassiterite and molybdenite. Wolframite is found in a single quartz-tourmaline-muscovite-topaz-pyrite vein, where it is partly replaced by scheelite. The quartz-tourmaline veins are subvertical, and are coincident with the northwest-trending pluton core.

Exploration by Carpentaria Exploration Company Ltd in 1970–71, including UV lamping, stream sediment, soil and costean rock sampling, defined a tungsten anomaly between Granite and Little Granite creeks. Apart from weak correlation of arsenic with tungsten, all other elements analysed were present at background levels. Biogeochemical prospecting (Quinn et al., 1974), utilising tree fern samples, showed good correlation of tungsten values with B-horizon soil samples.

Prospecting by CRA Ltd sought a flat-lying greisen in the roof zone (MacKenzie and Price, 1985), and soil sampling defined a 150 m long anomaly (>500 ppm W), within a 500 m isopleth of greater than 100 ppm W. Tungsten values in soil samples ranged up to 2800 ppm (threshold 500 ppm), and pan concentrates up to 5376 ppm (threshold 2800 ppm). Arsenic values correlated with tungsten, with up to 390 ppm As in soils. Peak float sample values of 0.6–1.3% WO_3 for well-mineralised greisen could not be repeated by systematic rock chip sampling. Analyses by Tulloch (in MacKenzie and Price, 1985) give low concentrations of tin: <5–15 ppm Sn in average Barrytown granite, 10 ppm Sn in greisen, and <5–30 ppm Sn in metasedimentary roof rocks.

Doctor Hill and Falls Creek: Scheelite mineralisation, located by pan prospecting and UV lamping, occurs in quartz-tourmaline veins in a biotite granite stock containing roof pendants of Greenland Group metasediments (Mackenzie, 1983; Maxwell, 1989). At Doctor Hill, scheelite distribution is patchy, and bears no relation to width or composition of veins, except that tourmaline is a consistent associated mineral. An area of mineralisation, 200 x 150 m, is defined by geochemical anomalies and high vein frequencies. Two diamond drill holes on the anomaly established that vein densities were maintained with depth, but scheelite content was low, with a best intersection of 0.3% WO_3 over 4.35 m (Maxwell, 1989).

At Falls Creek, 4 km to the north of Doctor Hill, scheelite mineralisation is exposed in a road cut, and is similar to the Doctor Hill prospect except that the biotite granite is weakly greisenised and locally pyritic, and many veins carry cassiterite (see Tin commodity report, page 9–15 this volume). One 145 m diamond drill hole gave best intersections of 0.4 m of 2% WO_3 and 0.3% Sn, and 0.3 m of 0.96% WO_3 and 0.49% Sn.

Skarn

No true tungsten skarn deposits are known, although suitable geological environments exist in Northwest Nelson where granodiorite of the Cretaceous Separation Point Batholith intrudes Paleozoic calcareous metasedimentary rocks in the Pikikiruna and Mt Arthur ranges. Some quartz-scheelite veins are associated with intrusives of granodiorite at Canaan (see below).

During the 1970s, Carpentaria Exploration carried out regional exploration for tungsten skarns in seven areas along the Separation Point Granite/Arthur Marble contact zone. Although no areas for follow-up work were located, the potential for tungsten was not fully tested because of analytical problems, and the use of standard stream sediment samples instead of the pan concentrate sampling methods now commonly used (Zuckerman, 1972a, 1972b).

Quartz-scheelite veins associated with Cretaceous granites

Several quartz-scheelite vein deposits are associated with granodiorite or porphyritic granite intrusions of the early Cretaceous Separation Point Suite in west Nelson.

Canaan: At Canaan in Northwest Nelson, scheelite-quartz veins cut a biotite granodiorite stock and adjacent diorite and marble (Williams, 1974). Scheelite is accompanied by pyrite, minor chalcopyrite, and rare galena and molybdenite (Climie, 1970). Bulk sampling gave grades of up to 6.87% WO_3, and a total tonnage estimate of 8750 t (Riley, 1966). Climie (1970) examined the Canaan scheelite prospect for Consolidated Silver, and estimated potential resources of some 8800 t at 0.38% WO_3, with visual estimates of up to 2% WO_3 in individual veins. Exploration in the Mt Pisgah area located nine veins (Zuckerman, 1972a).

Ngakawau: In the headwaters of the Ngakawau River, K-feldspar porphyry stocks along the Ngakawau Fault Zone contain vein stockworks with scheelite, pyrite, arsenopyrite and trace gold (Pirajno, 1982a; Riley, 1982).

Lake Stream: At Lake Stream in the Victoria Range, scheelite is found in hydrothermal quartz veins accompanied by pyrite, magnetite and minor molybdenite and chalcopyrite (Pirajno, 1982b). The veins are associated with metagabbro and porphyritic granite. Assay data indicate low concentrations of tungsten (0.25% WO_3).

Mesothermal quartz-scheelite veins

Mesothermal quartz lodes within the Marlborough, Alpine and Otago schists, contain scheelite, gold-scheelite, gold, gold-stibnite, stibnite or cinnabar. Most were mined for their gold content, but several produced significant tungsten. The lodes are developed along shear zones that are generally discordant to the foliation of the host schist.

Wakamarina: The Wakamarina field in Marlborough produced 475 t of concentrate at 65% WO_3 between 1874 and 1944 (Williams, 1974). Virtually all of the production came from the Golden Bar lode, mined mainly by the Dominion Consolidated Development Company (Johnston, 1992) between 1910 and 1923 for a return of 386 t of scheelite and 480 kg of gold from 101,357 t of ore (Skinner and Brathwaite, 1994).

The country rocks are low grade (prehnite-pumpellyite facies) schists, quartzite and metavolcanic greenschist of the Caples Terrane.

The Golden Bar lode lies within a steeply dipping normal fault. It was traced for about 1.8 km along strike, and was mined over a length of about 685 m, and to depths of 60 m in the Empire City section and 120 m in the Golden Bar section. The upper part of the lode consists of massive quartz, 1–3.6 m wide, but at a depth of about 60 m in the Empire City section the lode passes into crushed schist traversed by numerous quartz veinlets. The lode is composed of ribbon-banded quartz containing scheelite (<1%), minor pyrite (<1%), and rare gold and arsenopyrite (Skinner and Brathwaite, 1995). Underground exploration carried out by the Mines Department in the Golden Bar section towards Dead Horse Creek, over the period 1942–44, outlined over 6000 t of lode material, but tungsten and gold grades were considered too low to encourage further exploitation.

In Deep Creek, particularly on its north side at the Smile of Fortune Mine, scheelite was found in a number of quartz lodes. The area was investigated for scheelite in 1969–72 by Lime & Marble (Ball, 1972), and soil geochemical sampling was used to trace the poorly exposed scheelite-bearing quartz lodes.

Further north at Alford's (or Mountain Camp) Mine, a 0.6 m thick lode, dipping 45–25° northeast, was extensively prospected during World War I. Scheelite was found as thin veins or laminae parallel to the lode, as nodules up to 12 mm across, and, rarely, as lenses up to 2 m in length. A few tonnes of scheelite, hand picked from the lode, were exported. Underground exploration in 1937–40 showed that the reef pinched out with depth.

Wairau valley: Scheelite is present in many of the quartz lodes on the northern side of the Wairau valley in Marlborough (Johnston, 1993). Small quantities were mined in 1904–06 from the Sylvia lode on the Junction Spur in Top Valley, and during World War I, the waste dump was processed for its scheelite. The lodes on the Junction Spur were prospected before, and during, World War II but there was no production. In the 1970s, R.J. Whitehead reopened the Just for Luck Mine on the Junction Spur and prospected several other occurrences of scheelite (Whitehead, 1972). The most important prospect outside of the Junction Spur was the King John on the west side of Staircase Creek, a tributary of Top Valley Stream.

Glenorchy: In the Glenorchy area, Lake Wakatipu, west Otago, the schists contain metavolcanic greenschist, Fe-Mn bearing metachert and sulphide-rich pelitic schist, as well as quartzofeldspathic and pelitic schist (Williams, 1974, p. 416–420) of the Caples Terrane. The lodes consist of lensoid shear zones containing crushed schists and irregular quartz lodes. The lodes are gently dipping and cross cut schistosity in the enclosing schists at a high angle. The main minerals present in the lodes are quartz, scheelite, pyrite, arsenopyrite, calcite and magnetite (Batt, 1974). The total estimated production from 1881 to 1965 from the five main producing lodes on the Glenorchy Field was 2188 tonnes of scheelite concentrate (Mutch, 1969). Exploration by Alex Harvey Industries showed that the lode structures were discontinuous, with limited potential for additional scheelite resources (Fortune, 1972). The field was also assessed in the 1980s as a gold prospect (Cole, 1986).

Barewood: Scheelite is associated with gold mineralisation at Barewood, where three parallel, well-defined vein systems, about 1 km apart, are traceable for several kilometres (Finlayson, 1907, 1908; Williamson, 1939). They strike northwest and dip 45˚ to 70˚ to the northeast, cutting the flat-lying foliation in the schist. Each of these vein systems contains one main quartz-rich zone, up to 3 m thick, with thin (5–10 cm), subparallel stringers of quartz±scheelite in adjacent country rock. Some portions of the vein systems are composite stacks of sheared schist and vein quartz, separated by shear zones. Pyrite and arsenopyrite are the dominant sulphides but chalcopyrite, sphalerite, galena, and stibnite are also present (McKeag and Craw, 1989).

Although gold was produced at Barewood from 1890, scheelite was not recovered until 1907. From 1907 to 1917, 18 t were produced from 610 t of ore, and another 1 t was produced in 1943.

Macraes Flat: Scheelite is associated with the gold mineralisation at Macraes Flat in east Otago. Several subparallel quartz lodes were mined (1875–1936) for a production of about 1000 t of scheelite and 0.518 t of gold from 100 000 t of ore (1870–1954), mainly from the Golden Point Mine (Williamson, 1939).

Exploration in the late 1980s outlined a large low-grade gold deposit around the previously worked narrow lodes, and open pit mining began in late 1990. Because of its low price, scheelite is not recovered in this mining operation by Macraes Mining Company.

The gold-scheelite-quartz lodes are localised within a gently dipping, northwest striking regional shear zone (Finlayson, 1908; Williamson, 1939; Lee et al., 1989; McKeag et al., 1989; Teagle et al., 1990; Winsor, 1991). The shear zone is a low-angle thrust within psammitic schist. Local thickening of the shear zone (up to 125 m) has resulted from imbrication and stacking along moderate- to high-angle reverse faults within a duplex thrust fault structure (Teagle et al., 1990).

Scheelite is confined to lensoid quartz lodes, whereas gold also occurs in quartz vein stockworks, and with pyrite and arsenopyrite disseminations in sheared schist. The dominant alteration is silicification, with minor development of sericite and kaolinite.

Waipori: Several lodes worked for gold between 1861 and 1917, also produced small quantities of scheelite. The lodes dip at moderate angles and most strike north-northwest, although a few lodes in Stony Creek strike west-northwest. The lodes in the Stony Creek and Devils Creek areas were not significant gold producers, but one in Stony Creek produced 12 t of scheelite, and 4 t of concentrates were produced from the Deep Stream lode (Officers of New Zealand Geological Survey, 1970; Williams, 1974). No scheelite production was reported from the OPQ lode, the main gold-producing vein.

Stratabound scheelite

Lake Stanley: Stratabound scheelite mineralisation of possible synsedimentary-exhalative origin occurs near Lake Stanley (Northwest Nelson), hosted in marble lenses within the Cambrian Balloon Formation (Maxwell, 1983; Brathwaite and Pirajno, 1993). Scheelite is in streaks and lenses, each a few millimetres thick, within carbonate laminae that are interbedded with carbonaceous (?) or siliceous laminae. Stockworks of scheelite-bearing quartz veinlets are also present in some places and were probably formed by metamorphic remobilisation of the synsedimentary mineralisation.

The prospect was discovered and explored by Gold Mines of New Zealand (Maxwell, 1983). Seven holes were drilled with a best intercept of 0.28% WO_3 over 2.4 m, which apparently correlated with a surface zone assaying 1.3% WO_3.

Dansey Pass: Stratabound scheelite mineralisation is present at Dansey Pass, North Otago, in rocks of the Permian Dansey Metavolcanic Formation. This formation locally consists of basic metalavas, metatuffs, and associated metasediments, up to 760 m thick and with a 12 km strike length, conformably interbedded within quartzofeldspathic schists of the Haast Schist Group. Exploration by a Lime & Marble Ltd - Kennecott Explorations (Australia) Ltd joint venture (McClelland, 1981) and later by BP (Rutherford and MacKay, 1984), located two zones of scheelite mineralisation, one in a steep scree slope in the Otekaieke River gorge and another lying 500 m to the east of the gorge. Within the Otekaieke scree, mineralisation grading up to 1.3% WO_3 is found within a 1–3 m wide veined and sheared zone paralleling the trend of the metavolcanics. This narrow zone is bounded by a distinctive thin-bedded metabasite. Follow-up gridded soil surveys by BP located weak tungsten anomalies, ranging from 5 to 33 ppm W, along strike from the two mineralised zones, mostly in the mapped extensions of the metabasite. However, in-rock tungsten values from pits dug over the highest soil anomalies were generally 6 ppm W or less.

Kakanui Mountains: Exploration by BP of the metavolcanic units interbedded with Haast Schist of the Kakanui Mountains, southeast of Dansey Pass, located rare scheelite mineralisation restricted to small scale quartz veining, quartz segregations and coatings on joint planes (MacKay, 1984). Four of the 73 pan concentrate samples collected contained more than 20 ppm W, with a highest value of 568 ppm.

Stratabound and quartz vein scheelite in the Southern Alps

Reconnaissance exploration in the Southern Alps by CRA Exploration Pty Ltd, outlined an extensive zone containing weak scheelite mineralisation in a belt about 8 km wide and 60 km long, from Lake Hawea north to Mount Cook National Park (Purvis et al., 1982; Hawke and Price, 1983, 1989; Price et at., 1985). Scheelite is in quartz veins and segregations and is regionally localised to the vicinity of the pumpellyite-actinolite/greenschist facies boundary. It is commonly associated with calc-silicate and carbonate minerals. Occurrences of disseminated and bedding laminae-bound scheelite in chert and carbonaceous pelite were found in Long Flat and Scrubby Flat creeks, Hunter River area (Purvis et al., 1982). Wood (1983) also recognised widespread scheelite occurrences over a distance of 360 km in greenschist facies schist along the Southern Alps. He described the scheelite as occurring in disseminated spots, as well as in fine quartz veins. Craw and Norris (1991) considered that scheelite-quartz vein formation at Lake Hawea was synmetamorphic and represented tungsten mobilisation during metamorphism of the greywackes.

Thin quartz-calcite veins with minor biotite and sulphides, and traces of scheelite and gold, have been described by Craw et al. (1987) from the Callery River area, 25 km northeast of Mount Cook. These veins crosscut post-metamorphic folds in greenschist facies schist, and are considered to be related to late Cenozoic deformation associated with rapid uplift along the Alpine Fault which allowed hot (250–320˚C) metamorphic fluids to reach relatively shallow (4–5 km) crustal levels.

Placers

Small alluvial deposits containing detrital scheelite and gold were worked at Glenorchy and Macraes Flat, producing 15 t (1862–1964) and 36 t (1870?–1968) respectively. The fine grain size of the scheelite made recovery difficult and inefficient.

Trace quantities of detrital scheelite are widespread in Quaternary alluvial gravels of Westland and Marlborough but no economic deposits are known (Henderson, 1917; Morgan, 1927; Hutton, 1950; MacDonald, 1965; Bradley et al., 1979; Minehan, 1989).

Past Production, Resources and Future Potential

New Zealand production of scheelite concentrate to the end of 1988 was of 3828 t. The Macraes deposit produced 1000 t of concentrate between 1875 and 1936, and 475 t of concentrate came from the Wakamarina field between 1874 and 1944. Most of the balance (2353 t) has come from the Glenorchy field.

Limited resources exist at Glenorchy, but they are subeconomic at current depressed tungsten prices. At Macraes, the tungsten resource has not been assessed because scheelite is not worth recovering at current prices.

Future Trends

Demand for tungsten is likely to continue at similar levels. Increased demand related to development in the world economy may be partly offset by substitution. Reid (1989) noted that coatings (aluminium oxide, titanium oxide, titanium nitride) have improved the cutting and wear resistance of cemented tungsten carbide tool inserts, and that coating use is expected to increase. The extended wear of inserts decreases the rate of replacement, and thus the growth of tungsten consumption. In addition there will be a slow increase in substitution of tungsten-based materials by ceramic and polycrystalline diamond-surfaced cutting tools and wear parts.

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