MINERAL RESOURCES BULLETIN 22

Department of Industry and Resources

TANTALUM IN WESTERN AUSTRALIA

by J. M. Fetherston

Geological Survey of Western Australia

TANTALUM IN WESTERN AUSTRALIA

FRONTISPIECE:
Historic pump at the Wodgina tantalum–tin mine. Brought from Port Hedland by camel train about 1905, this vintage steam pump was used for many years pumping water and providing motive power for ore crushing

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Perth 2004

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Cover photograph:
A rosette of manganotantalite crystals from Moolyella, Pilbara region. Simpson Collection, Western Australian Museum. Specimen is approximately 6 cm in diameter

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Tantalum in Western Australia

by

J. M. Fetherston

Abstract

Tantalum is a hard, dense, blue-grey metal with a melting point of 2996°C that combines readily with other refractory metals to form 'super alloys'. It has high tensile strength, is extremely malleable and ductile, and is almost completely immune to chemical attack. Tantalum is present in a vast array of minerals; however, it is tantalite, a member of the columbite–tantalite group, that is the most commonly occurring tantalum mineral.

Tantalum was first discovered in Western Australia in 1893 at Greenbushes in the southwest of the State and in 1904–05 around Wodgina in the Pilbara region. Over the first 40 years tantalite was mined as a byproduct of the tin-mining industry. During the Second World War new electronic applications for tantalum were developed that triggered a new round of exploration. In the early 1980s, detailed exploration at Greenbushes and later at Wodgina revealed the huge tantalum resources present in these deposits.

In Western Australia, tantalum is found in three distinct primary mineralization styles. Of these, granitic rare-metal pegmatites are almost exclusively the dominant style, with the only exceptions being the carbonatite style of the Mount Weld deposit, and the subalkaline granite–syenite style of the Brockman deposit. Economic tantalum mineralization is mostly found in highly fractionated granitic rare-metal pegmatites commonly derived from late Archaean granites. These pegmatites are commonly situated on regional shears and are typically hosted by greenstone rocks within 5–10 km of the parent granite. Fractionated pegmatites may contain multiple concentric zones, or stacked sheets containing areas of discrete mineralization rich in tantalum, tin, niobium, lithium, beryllium, and caesium. In Western Australia, most pegmatites have been subject to deep weathering and extensive kaolinization up to 80 m in depth. In many areas weathering and erosional processes have formed economic eluvial, colluvial, and alluvial placer tantalum deposits.

Currently, Western Australia has four operating tantalum mines. The Greenbushes and Wodgina mines are the largest and second-largest tantalum operations in the world respectively, with combined reserves and resources totalling over 310 Mt at an average grade of 0.025% Ta_2O_5. Two other mines are located at Bald Hill in the Eastern Goldfields and at Dalgaranga near Mount Magnet. It is estimated that the State has at least 75% of presently defined global tantalum reserves.

Tantalite ore is processed into export-grade concentrate averaging 30–35% Ta_2O_5. In 2001, Western Australia exported 806 t of concentrate, valued at A$176.3 million, primarily to the USA, Germany, and Japan for processing into tantalum metal and powder. The manufacture of tantalum metal accounts for only 39% of total output. Tantalum metal is used in the chemical industry for its anti-corrosive properties, and as tantalum carbide in metal cutting and machining. It has also found new applications in the aerospace industry as 'super alloys', and in medicine and dentistry.

At least 61% of Ta_2O_5 high-grade concentrate is used in the manufacture of high-purity tantalum powder primarily for the manufacture of tantalum capacitors required by the electronics and telecommunications industries. Due to their small size and high reliability, these capacitors are used in miniaturized circuits of computerized equipment. It is estimated that 35% of tantalum capacitors are destined for use in mobile (cellular) phones.

Since 1980, tantalum has been subject to several periods of increased demand and rapid price escalations, which have been followed by rapid reversals in demand and a subsequent crash in price. This volatility in the market was originally attributed to panic buying and inventory hoarding in times of short supply. Today, the market is also affected by changes in demand by the electronics industry. This was effectively demonstrated by the all-time-high spot prices reached in 2000 that were soon followed by a rapid fall off in demand and a subsequent price crash in 2002. Since that time there have been indications of a modest resurgence in demand.

Western Australia has numerous highly prospective areas for the future development of tantalum resources. Many of these areas in the south of the State, such as Cattlin Creek, North Ravensthorpe, Binneringie, Mount Deans, and extensions to Bald Hill, have already been fully or partially explored. In the north of the State, areas around Dalgaranga, Arthur River, and in the Pilbara region, particularly in the Wodgina area, already have established resources or demonstrated high prospectivity. The large tantalum resources contained in the Mount Weld and Brockman deposits await the development of improved ore-processing technology.

With the probable return to increased shipments of tantalum concentrates in 2003, it is expected that the expanding electronics and communications industries should provide the necessary impetus for a resurgence in demand, together with increased prices, within a few years. At that time, the State's existing tantalum operations, plus many areas prospective for tantalum, will be at the forefront of future exploration and development thus maintaining Western Australia's position of world leader in the mining and processing of this high-tech metal.

KEYWORDS: Western Australia, mineral resources, Greenbushes, Wodgina, Bald Hill, Dalgaranga, Mount Weld, Brockman, mineral deposits, Capricorn Orogen, Halls Creek Orogen, Pilbara Craton, Yilgarn Craton, columbite, tantalite, mineral processing, tantalum, capacitors, mineral economics.

Chapter 1

Introduction

Object and scope

The need for a new Bulletin on the tantalum industry in Western Australia was first contemplated in 2001 at a time when world prices for tantalum had reached unprecedented highs, and Western Australia was leading the world with the largest developed tantalum resources and supplying close to 45% of world output of high-grade tantalum concentrate. In addition to high prices and exceptional demand for this high-tech metal, especially by the electronics and telecommunications industries, came two new mines and a surge of mineral exploration by many companies keen to investigate and possibly develop the numerous tantalum prospects and localities around the State.

Since a publication on the State's tantalum resources had not been produced in almost 60 years, it was considered timely that another Bulletin be written to record the substantial changes to the industry that have taken place over time, and the massive exploration effort currently underway. This was to be set in the context of the world tantalum industry in terms of raw material manufacture, industrial applications, world economics, and global tantalum resources.

During this Bulletin's preparation, world demand for tantalum has declined sharply and prices have crashed. This is largely attributed to a reduction in demand by the electronics and telecommunications industries due to an oversupply situation in the international supply chain. As this publication goes to press, Sons of Gwalia Limited, the worlds's largest supplier of tantalum concentrate, expects that the oversupply situation should work its way out during the year, driven by these expanding industries. This being so, it is expected that increased demand will return within a few years and with it a renewed interest in tantalum exploration in the State.

It is intended that this Bulletin will provide the reader with a general knowledge of the tantalum industry, as well as a comprehensive account of current tantalum reserves, resources, and prospectivity in Western Australia.

Sources of information

Sources of information used in this Bulletin are from both published and unpublished data, supplemented by information gathered on field inspections. Published information is derived from Geological Survey of Western Australia (GSWA) Records, Reports, Bulletins, annual reports, and geological maps. Other published sources include company quarterly and annual reports, papers in geoscience and other scientific journals, conference papers, and articles published in newspapers and mining magazines.

Unpublished information has been obtained from open-file statutory reports submitted to the Department of Industry and Resources (DoIR) by various mineral exploration companies. This is supplemented by university theses, unpublished reports to the Australian Stock Exchange, unpublished data made available by tantalum mining companies, and information, both local and international, available on the internet. Key websites accessed for this Bulletin are listed in Appendix 1.

During field inspections, a number of samples from significant sites were selected for chemical analysis for major and trace elements by ICP mass spectrometry, or optical emission spectrometry. Mineral identification was carried out using X-ray powder diffraction, and by energy dispersive X-ray analysis on a scanning electron microscope. Results of these tests are provided in the discussion of the sites where the samples were taken. The localities of the tantalum deposits, prospects, and occurrences in Western Australia discussed in this Bulletin are given in Appendix 2.

System of units

The units used in this Bulletin follow the International System of Units or SI system that has been in use in Australia for many years. However, it should be noted that the internationally accepted unit of weight for tantalum metal and Ta_2O_5 ore, concentrate, and powder traded on the international market is pounds, a non-standard SI unit.

If the reader should wish to convert from SI values used in this Bulletin, expressed in tonnes (t), to pounds weight (lb), then it will be necessary to multiply the value expressed in tonnes by a factor of 2205.

Abbreviations

A$	Australian dollars
Ga	billion years
Ma	million years

Mm^3	million cubic metres
Mpa	megapascals
µm	micrometre
Mtpa	million tonnes per annum
REE	rare earth elements

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The author gratefully acknowledges the extensive assistance given by the Western Australian mining industry in the preparation of this Bulletin. In particular, thanks are extended to Mr Peter Lalor, Executive Chairman of Sons of Gwalia Limited, Mr Colin McCavana, President of Haddington Resources Limited, and Mr Michael Fotios, Managing Director of Tantalum Australia NL, for making available company resources and information for this project. On site assistance given by management and professional staff at Greenbushes, Wodgina, Bald Hill, and Dalgaranga mine sites is also much appreciated. Thanks are extended to company geologists Mr Harry Cornelius of Sons of Gwalia, Mr Dale Brittliffe of Tantalum Australia, and Mr Rob Duncan of Lynas Corporation Limited for their ongoing assistance, valuable discussions, and feedback during the writing of the manuscript. The assistance of Dr Alex Bevan and Mr Geoff Deacon of the Western Australian Museum is appreciated for access to the Simpson Collection and for the provision of tantalum mineral imagery.

Chapter 2

Properties and mineralogy

Properties of tantalum

Tantalum (Ta) is a very hard, dense, blue-grey, refractory metal belonging to Group Vb of the periodic table, together with vanadium (V) and niobium (Nb). Refractory metals are those with a very high melting point, generally above 1900°C. Tantalum has a cubic crystalline structure, a very high melting point of 2996°C, and is a good conductor of heat and electricity (Lide, 1996; Spectrum Laboratories Inc., 2003; The Rembar Company Inc., 2003; Espi Metals, 2002). It combines readily with other refractory metals such as tungsten (W), titanium (Ti), and hafnium (Hf) to form alloys with high-temperature strength and stability properties. Pure tantalum has a high tensile strength, is extremely malleable and ductile, and is easily worked into intricate forms at room temperature. Under these conditions it can be drawn into a very thin wire or may be fabricated by bending, roll forming, welding, and a number of other processes. The more common physical properties of tantalum are given in Table 1.

Tantalum is almost completely immune to chemical attack below 150°C, as it forms a protective oxide film on its surface. However, it is slowly attacked by alkalis, resulting in hydrogen absorption that may cause hydrogen embrittlement. Hydrogen embrittlement is a process where free hydrogen reacts with a metal, forming hydrides that tend to reduce the metal's strength. Below 150°C, tantalum is attacked only by hydrofluoric acid, fuming sulfuric acid, or strong alkalis (Table 2). At high temperatures the metal becomes much more reactive. For example, at temperatures greater than or equal to 300–400°C tantalum reacts with oxygen and nitrogen in the atmosphere.

Table 1. Physical properties of tantalum

Atomic number	73
Atomic weight	180.95
Valences	+2, +3, +4, and +5
Naturally occurring isotopes	Tantalum–181 (99.9877%) Tantalum–180 (0.0123%)
Density (at 20°C)	16.654 g/cm^3
Melting point	2996°C
Boiling point	5425°C
Recrystallization temperature	1204°C
Coefficient of thermal expansion (at 20°C)	6.5 × 10^{-6}/°C
Specific heat capacity (at 25°C)	0.140 J/g/°K
Thermal conductivity (at 27°C)	0.575 W/cm/°K
Electrical resistivity (at 20°C)	13.5 microhms/cm
Tensile strength (room temperature)	240–480 Mpa
Refractive index	2.05

SOURCES: Lide (1996); Espi Metals (2002); Spectrum Laboratories Inc. (2003); The Rembar Company Inc. (2003)

NOTES: J/g/°K joules per gram per degree kelvin
W/cm/°K watts per centimetre per degree kelvin
Mpa megapascals

Table 2. Comparative corrosion rates of refractory metals

Corrosive agent	*Concentration (%)*	*Temperature (°C)*	*Corrosion rates of refractory metals* *Tantalum*	*Niobium*	*Titanium*	*Zirconium*
				mm/year		
Acetic acid	50	100	nil	nil	nil	nil
Bromine	dry	93	nil	nil	attacked	nil
Chlorine	wet	104	nil	nil	nil	0.254
Chlorine acid	50	100	nil	0.025	0.127	0.127
Hydorchloric acid	5	93	nil	0.025	<2.540	nil
Hydrochloric acid	30	93	nil	0.127	rapid	nil
Nitric acid	65	100	<0.051	<0.051	<0.051	<0.051
Sodium hydroxide	10	room	a	a	nil	nil
Sulfuric acid	40	100	nil	0.508	rapid	0.076
Sulfuric acid	98	100	<0.051	attacked	rapid	<5.080

SOURCE: Cosica (2003)

NOTE: a Presence of hydrogen may make material become brittle

Tantalum and niobium are often found together in the same ores due to their very similar chemical properties, with niobium often being far more abundant than tantalum. This ratio is attributed to the fact that in the earth's crust niobium is approximately ten times more abundant than tantalum. However, in Western Australia, tantalum is generally more abundant than niobium due to the relative abundance of rare-metal tantalum-rich pegmatites.

Tantalum mineralogy

Tantalum is an element that is present naturally in a vast array of mainly oxide minerals. These minerals range from commonly occurring tantalum ore minerals, generally with simple crystalline structures, to complex and often relatively rare minerals. Of all the tantalum-bearing mineral groups, columbite–tantalite [$(Fe,Mn)(Ta,Nb)_2 0_6$] is the most widespread and contains the most important ores of tantalum.

Due to their similar properties of ionic radius, valence, and electronegativity, tantalum and niobium (also known as columbium) occur together in many isomorphous mineral series, the best known of these being the columbite–tantalite group. An isomorphous mineral series is a series of minerals with similar chemical composition that crystallize in the same crystal system and differ from each other by cation substitution without alteration of the crystal form. In addition, dimorphic relationships exist between some tantalum mineral groups as is the case between the columbite–tantalite group and the tapiolite series. Dimorphic relationships occur where minerals with identical chemical composition crystallize in two different crystal systems.

Tantalum can also substitute for cations in other minerals, such as for tin (Sn) in cassiterite, titanium in rutile (e.g. strüverite) and ilmenite, and for various cations in wolframite and a number of phosphate minerals. In addition, niobium and tantalum may replace titanium or zirconium to form many comparatively rare silicate minerals.

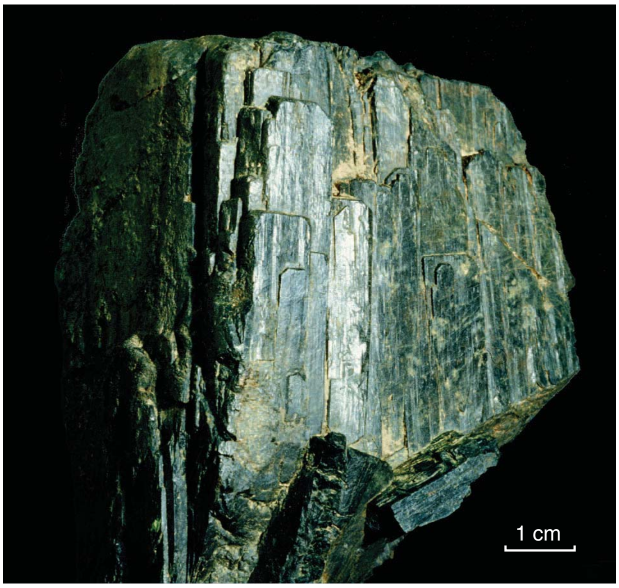

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Figure 2. A large tantalite specimen displaying elongated, parallel prisms. Collected at Wodgina (Simpson Collection, Western Australian Museum)

A broad classification of the commonly occurring tantalum mineral groups and series, and other significant tantalum minerals, is shown in Tables 3 and 4. A full classification of tantalum mineralogy has been given in Cerny and Ercit (1989), and all tantalum minerals have been described in detail in Gaines et al. (1997). A detailed description of tantalum minerals found in Western Australia may be found in Miles et al. (1945).

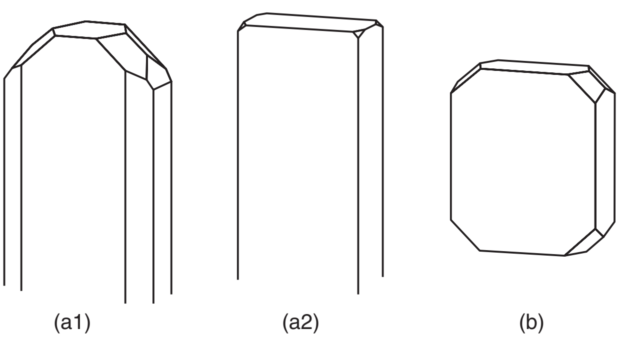

Figure 1. Common crystal habits of tantalite minerals: a1) short, blocky, rectangular tantalite prism with complex pyramidal terminations; a2) short, blocky, rectangular manganotantalite prism (this is the typical form found at Wodgina); b) flat, tabular tantalite plate. Plates may be aggregated in parallel masses (modified from Miles et al., 1945)

Tantalite minerals

Tantalite, an iron–manganese–tantalum–niobium oxide with the chemical formula $(Fe,Mn)(Ta,Nb)_2 0_6$, is by far the most commonly occurring tantalum mineral throughout the world. This is particularly so in Western Australia where tantalite and its sister mineral manganotantalite are the dominant tantalum ores. Physical characteristics for these minerals are given in Table 5, and three common crystal forms are shown in Figure 1. A large tantalite specimen from Wodgina, displaying elongated parallel prisms, is shown in Figure 2.

Stibiotantalite ($SbTaO_4$), a closely related mineral which occurs in the Greenbushes area in the southwest of the State, exhibits similar physical characteristics to those of tantalite, particularly in crystal form, but differs in colour (greenish-white to pink to almost black), lower specific gravity (6.1 – 7.3), and hardness (5 – 5.5). In the

Table 3. Summary of tantalum mineral groups and series

Tantalum group or series	*General formula*	*Crystal system*	*Minerals*	*Chemical formula*	*Paragenesis of mineral group or series*
Columbite–tantalite group	$(Fe,Mn)(Ta,Nb)_2O_6$	Orthorhombic	Ferrotantalite Manganotantalite Manganocolumbite Ferrocolumbite Magnocolumbite	$(Fe,Mn)(Ta,Nb)_2O_6$ $(Mn,Fe)(Ta,Nb)_2O_6$ $(Mn,Fe)(Nb,Ta)_2O_6$ $(Fe,Mn)(Nb,Ta)_2O_6$ $(Mg,Fe,Mn)(Nb,Ta)_2O_6$	Minerals in this group occur in: granitic rare-metal pegmatites, rare-metal (Li–F) granites, peralkaline granites/syenites, deeply weathered deposits, placer deposits
Tapiolite series	$(Fe,Mn)(Ta,Nb)_2O_6$	Tetragonal	Ferrotapiolite Manganotapiolite	$(Fe,Mn)(Ta,Nb)_2O_6$ $(Mn,Fe)(Ta,Nb)_2O_6$	Minerals in this series occur in granitic rare-metal pegmatites
Ixiolite group	$(Ta,Nb,Sn,Fe,Mn,Ti)_4O_8$	Orthorhombic	(Stannian) ixiolite Titanian ixiolite (also W- and Sc-rich varieties)	$(Ta,Nb,Sn,Fe,Mn,Ti)_4O_8$ $(Ta,Ti,Nb,Mn,Fe,Sn)_4O_8$	Minerals in this group occur in granitic rare-metal pegmatites, [peralkaline granites/syenites]
Wodginite group	$(Mn,Sn,Fe^{2+},Ti,Li)Ta_2O_8$	Monoclinic	Wodginite Ferrowodginite Titanowodginite Lithiowodginite	$MnSnTa_2O_8$ $Fe^{2+}SnTa_2O_8$ $MnTiTa_2O_8$ $LiTa_3O_8$	Minerals in this group occur in granitic rare-metal pegmatites
Stibiotantalite group	$Sb(Ta,Nb)O_4$	Orthorhombic	Stibiotantalite Bismutotantalite Stibiocolumbite	$SbTaO_4$ $Bi(Ta,Nb)O_4$ $SbNbO_4$	Minerals in this group occur in granitic rare-metal pegmatites
Foordite–thoreaulite series	$Sn(Nb,Ta)_2O_6$	Monoclinic	Foordite Thoreaulite	$SnNb_2O_6$ $SnTa_2O_6$	Minerals in this series occur in granitic rare-metal pegmatites
Pyrochlore group	$A_{1-2}B_2O_6(O,OH,F).nH_2O$ where: A = Ca, K, Ba, Y, Ce, Pb, U, Sr, Cs, Na, Sb^{3+}, Bi, Th B = Ta, Nb, Ti, Sn, Fe, W	(commonly metamict) Isometric	Pyrochlore Betafite	$(Na,Ca)_2Nb_2O_6(OH,F).nH_2O$ $(Ca,Na,U)_2(Ti,Nb)_2O_6(OH)$	Minerals in this group occur in: carbonatites, miaskitic nepheline syenites, peralkaline granites/syenites
			Microlite	$(Na,Ca)_2Ta_2O_6(O,OH,F)$	Rare metal (Li–F) granites, and granitic rare-metal pegmatites
Fergusonite group	ABO_4 where: A = Y, Er, Ce, La, Nd, Dy, U, Zr, Th, Ca, Fe^{2+} B = Nb, Ta, Ti, Sn, W	(commonly metamict) Monoclinic Tetragonal Orthorhombic Orthorhombic	β-Fergusonite-(Y) Formanite Yttrotantalite Yttrocolumbite	$YNbO_4$ $YTaO_4$ $(Y,U,Fe^{2+})(Ta,Nb)O_4$ $(Y,U,Fe)(Nb,Ta)O_4$	Minerals in this group occur in: peralkaline granites/syenites, carbonatites, [rare-metal (Li–F) granites], [granitic rare-metal pegmatites]
Euxenite group	AB_2O_6 where: A = Y, Ca, Ce, U, Th B = Nb, Ta, Ti	(commonly metamict) Orthorhombic Orthorhombic Orthorhombic	Euxenite Tanteuxenite Polycrase	$(Y,Ca,Ce)(Nb,Ta,Ti)_2O_6$ $(Y,Ca,Ce)(Ta.Nb,Ti)_2(O,OH)_6$ $(Y,Ca,Ce,U,Th,)(Ti,Nb,Ta)_2O_6$	Minerals in this group occur in: peralkaline granites/syenites, [rare-metal (Li–F) granites], [granitic rare-metal pegmatites]
Aeschynite series	$(Ce,Ca,Fe,Y,REE)(Nb,Ta,Ti)_2O_6$	Orthorhombic	Aeschynite Tantalaeschynite	$(Ce,Ca,Fe)(Ti,Nb)_2(O,OH)_6$ $(Ca,REE)(Ta,Ti,Nb)_2O_6$	Minerals in this series occur in: peralkaline granites/syenites, miaskitic nepheline syenites, [carbonatites], [granitic rare-metal pegmatites]

SOURCE: Cerny and Ercit (1989)

NOTES: REE rare earth element
[ ] subordinate paragenetic relationship

past, prospectors often mistook stibiotantalite for rutile. An example of rounded alluvial stibiotantalite from Greenbushes is shown in Figure 3.

Tantalite indicators

In the field, the best indicators for identifying tantalite and manganotantalite are:

- Mineral associations in pegmatites and acid granites — albite, spodumene, cassiterite, microcline, lepidolite, apatite, beryl, muscovite, microlite, tourmaline, and amblygonite;
- Specific gravity — tantalite in a reasonably pure form has a much higher specific gravity (maximum 8.1) than most minerals. It may be easily identified from cassiterite (tin ore) with a specific gravity of 6.5 – 7.0, and from much lighter iron-oxide pebbles or nodules. This property is particularly important in the mining of alluvial and eluvial tantalite deposits. However, care must be exercised with manganotantalite as the difference in specific gravity compared to cassiterite is not as marked;
- Streak — typically, tantalite has a black to dark reddish-brown streak, whereas cassiterite's streak is typically white;
- Crystal habit — tantalite often displays distinctive short, stubby prismatic crystals;
- Combined with the usual black colour and sub-metallic to resinous lustre, and any of the above physical characteristics, tantalite may be reasonably easily identified.

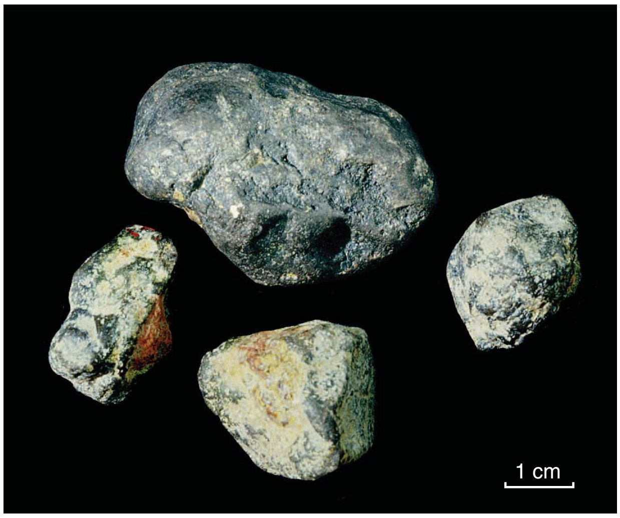

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Figure 3. Rounded, alluvial stibiotantalite from Greenbushes (Simpson Collection, Western Australian Museum)

For a positive identification of tantalite minerals, specimens should always be sent for chemical analysis and other laboratory tests as required, such as X-ray diffraction, scanning electron-microscope mineral analysis, or description of polished thin sections.

Chemical analyses for samples of Western Australian tantalite, manganotantalite, stibiotantalite, and wodginite are given in Table 6.

Table 4. Summary of other significant tantalum minerals

Other significant tantalum minerals	*Chemical formula*	*Crystal system*	*Paragenesis*
Fersmite	$Ca(Nb,Ta)_2O_6$	Orthorhombic	Peralkaline granites/syenites, miaskitic nepheline syenites, [carbonatites]
Loparite	$(Ce,Na,Ca)_2(Ti,Nb,Ta)_2O_6$	Isometric	Agpaitic nepheline syenites
Samarksite	$(Y,Fe,U)(Nb,Ta)O_4$	Orthorhombic (always metamict)	Peralkaline granites/syenites, [rare-metal (Li–F) granites], [granitic rare-metal pegmatites]
Simpsonite	$Al_4(Ta,Nb)_3O_{13}(OH)$	Hexagonal	Granitic rare-metal pegmatites
Strüverite	$(Ti,Ta,Nb,Fe^{3+},Fe^{2+})O_2$	Tetragonal	Rare-metal (Li–F) granites, granitic rare-metal pegmatites, [peralkaline granites/syenites], placer deposits
Secondary tantalum oxides			
Natrotantite	$Na_2Ta_4O_{11}$	Hexagonal	Granitic rare-metal pegmatites
Calciotantite	$Ca(Ta,Nb)_4O_{11}$	Hexagonal	Granitic rare-metal pegmatites
Alumotantite	$AlTaO_4$	Orthorhombic	Granitic rare-metal pegmatites
Lithiotantite	$Li(Ta,Nb)_3O_8$	Monoclinic	Granitic rare-metal pegmatites
Tantite	Ta_2O_5	Triclinic	Granitic rare-metal pegmatites

SOURCE: Cerny and Ercit (1989)
NOTE: [ ] Subordinate paragenetic relationship

Table 5. Physical characteristics of tantalite

Colour	Black to dark brown or even reddish brown
Lustre	Submetallic to almost resinous
Transparency	Opaque
Crystal system	Orthorhombic
Crystal habit	Short, blocky rectangular prisms with or without complex prismatic terminations or as flat tabular plates that may form parallel aggregations May form interpenetration twins. Also forms large wedge- or fan-shaped masses
Cleavage	Good in one direction
Fracture	Subconchoidal to uneven
Hardness	6 – 6.5 (brittle)
Specific gravity	8.1 (pure form)
Streak	Black to brownish red
Solubility	Insoluble in HCl
Other characteristics	Crystals may be coated with a bluish iridescent film, are sometimes striated, and may show weak magnetism
Mineral associations	Albite, spodumene, cassiterite, microcline, lepidolite, apatite, beryl, muscovite, microlite, tourmaline, and amblygonite
Field indicators	Mineral associations, specific gravity, streak, and crystal habit

SOURCES: Gaines et al. (1997); Mondadori (1977)

Table 6. Chemical analyses of four tantalum minerals from Western Australia

	Tantalite (Enterprise Claim Greenbushes[(a)])	*Manganotantalite (Wodgina[(a)])*	*Stibiotantalite (Greenbushes[(a)])*	*Wodginite (Wodgina[(b)])*
		Percentage		
Ta_2O_5	75.87	69.63	51.95	70.49
Nb_2O_5	2.89	12.38	4.49	7.63
TiO_2	0.27	0.25	–	–
SnO_2	4.96	0.90	–	8.92
FeO	9.53	2.05	–	1.34
Fe_2O_3	1.28	0.04	0.39	–
MnO	3.51	12.71	trace	10.87
CaO	0.00	1.63	–	0.42
MgO	0.00	0.10	–	0.37
Na_2O	–	trace	–	–
Sb_2O_3	trace	–	38.04	–
Al_2O_3	1.00	0.01	–	–
SiO_2	0.64	0.36	3.14	–
NiO	–	–	trace	–
Bi_2O_3	–	–	0.79	–
CuO	–	–	0.20	–
H_2O	0.59	0.31	0.61	0.18
Total	**100.54**	**100.37**	**99.61**	**100.22**
Specific gravity	7.47	6.83 – 7.01	6.47	–

SOURCES: (a) Miles et al. (1945)
(b) Nickel et al. (1963)

NOTE: – not analysed

Chapter 3

A brief history of tantalum and development of the industry in Western Australia

A brief history of tantalum

The element tantalum was discovered in 1802 by Swedish chemist Anders Ekeberg from mineral specimens he collected in Sweden and Finland. Ekeberg proposed the name tantalum after the Greek mythological character Tantalus, as he observed that tantalum oxide (Ta_2O_5) did not react with acids to form salts and therefore it 'cannot quench its thirst — just like Tantalus in the Underworld'. It is also worth noting that tantalum's sister element niobium (also known as columbium), discovered only one year before, was named after Niobe, daughter of Tantalus (Lide, 1996; Spectrum Laboratories Inc., 2003; Cosica, 2003).

So similar are these two elements that for over 40 years many chemists considered tantalum to be an allotropic form of niobium. In 1844, Heinrich Rose found both elements present in a single specimen of columbite, and in 1866 Jean-Charles Galissard de Marignac demonstrated that niobic and tantalic acids were two different liquids. At that time, chemists were only able to isolate the impure metal, and it was not until 1903 that Werner von Bolton was able to produce relatively pure ductile tantalum metal.

In 1905, the first commercial use of tantalum began in Germany, with the invention by Siemens and Halaske of metal filaments in incandescent light globes, where tantalum wire was used to replace carbon filaments that were in use at that time. This application for tantalum was comparatively short-lived, as by 1909 tungsten filaments were beginning to replace those made of tantalum, and by 1912 the substitution by tungsten filaments had been completed.

From this time until the 1940s, research was largely directed into possible applications of the unique physical and chemical properties of tantalum, with its extremely high melting point (2996°C), strength, ductility, and its corrosion resistance to most strong acids. As a result of this research, applications for tantalum were found in the metallurgical and chemical industries, with the development of special alloys and corrosion-resistant chemical-processing equipment. Tantalum even found use as an economic substitute for some applications for platinum. In 1929 tantalum carbide, one of the hardest artificial substances known to man, was developed in the United States for use in cutting tools.

It was not until the advent of the Second World War in the 1940s, when 'wet' and later 'solid' tantalum capacitors were developed for use in military communication and early radar equipment, that the tantalum industry was assured. At that time, Australia was the world's largest tantalum producer. In the early 1950s the United States, having comparatively small natural tantalum resources, began to acquire a strategic stockpile of almost 7000 t of tantalum and niobium mineral oxides. The policy of strategic stockpiles created a new demand for tantalum and led to the discovery of large, but mainly low-grade, tantalum deposits around the world.

The period from 1960 to 1979 was one of fluctuating supply and demand, largely brought about by new applications for tantalum mainly in the electronic, chemical, aerospace, and toolmaking industries. During this period, prices for the metal fluctuated wildly from a low of approximately US$12/kg in 1962 to over US$242/kg at the beginning of the 1980s.

In 1974, the Tantalum–Niobium International Study Center (TIC) was founded in Brussels, Belgium. This international, non-profit association was set up to represent the interests of the tantalum–niobium industry, and to the present day provides information about tantalum and the tantalum industry. The TIC also publishes lists of member companies involved in tantalum mining and manufacturing around the world (Tantalum–Niobium International Study Center, 2002).

In the 1980s, demand for tantalum accelerated rapidly, with the invention of the microchip tantalum capacitor leading to its widespread application in computers, communications, and other electronic equipment. It was this impetus that led to the development of hard-rock tantalum mining and to the evolution of the large-scale openpits in operation today, notably in Western Australia.

Today, the tantalum industry is a multi-billion dollar industry worldwide, and is growing from strength to strength with the development of more sophisticated electronic applications, as well as new applications in the metallurgical industry, such as high-tech tantalum alloys used in turbine blades in the aerospace and power generation industries.

Development of the tantalum industry in Western Australia

The tantalum industry in Western Australia had its beginnings with the discovery of tin–tantalum pegmatite bodies (and their associated hydrothermal veins), and alluvial and eluvial deposits in many areas of the State. Tin was first discovered in the Greenbushes area in the South West region in 1886 by a prospector, D. W. Stinton, following advice from Government Geologist E. T. Hardman who had previously carried out a geological survey in the area. Stinton subsequently became the first owner of a 400-acre mining lease at Greenbushes and mining commenced in 1888. He was also the founder of the Bunbury Tin Mining Company.

In 1888 in the Pilbara region, tin was discovered in many streams between the Yule and Coongan rivers near Marble Bar by prospectors moving south from the east Kimberley goldfields. Further exploration identified numerous prospects and by 1902 alluvial tin was being produced from three centres in the region. Significant tin production continued until 1920, principally from the Moolyella, Shaw River, Coondina and Wodgina tin fields (Hickman, 1983).

In 1893, stibiotantalite was the first tantalum mineral to be identified in Western Australia at Greenbushes. Following this in 1900, tantalite was found in Greenbushes alluvial ore. In 1904–05 manganotantalite, mangano-columbite, and microlite were reported from Wodgina, and microlite was also discovered at nearby McPhees Range (Miles et al., 1945). Simpson (1909) recognized a manganese-rich mineral from Wodgina as ixiolite. This was later formerly identified as wodginite by Nickel et al. (1963). Wodgina is now recognized as the type locality for this important tantalum mineral (Fig. 4).

The presence of tantalum mineralization, together with tin in hard-rock pegmatites and associated alluvial–eluvial deposits, was a problem in many of the early workings. At that time, tantalum minerals had no economic value and tin miners of the 1890s were penalized by smelting companies for the level of tantalum present in their tin ore.

Tantalum production commenced in 1905 following the invention of the tantalum incandescent light filament. This production was principally from Wodgina, which met about 80% of world demand, not only during the period of demand for tantalum filaments (until about 1910), but up until the Second World War through periods of somewhat sporadic demand. Most production at Wodgina was sourced from alluvial and eluvial workings, with minor production from small underground and openpit workings from the main-lode pegmatite. Towards the end of the 1920s, there was a revival of interest with the discovery of new uses for tantalum that led to the discovery of new tantalum prospects and increased mining activity.

The start of the Second World War saw a resurgence in demand for tantalum. As a consequence there was significant production from alluvial and eluvial deposits, as well as hard-rock pegmatite deposits, at Wodgina and the other Pilbara locations of Strelley and Tabba Tabba to meet this demand. Towards the end of the war, tantalum was produced as a strategic metal by the Australian Federal Government.

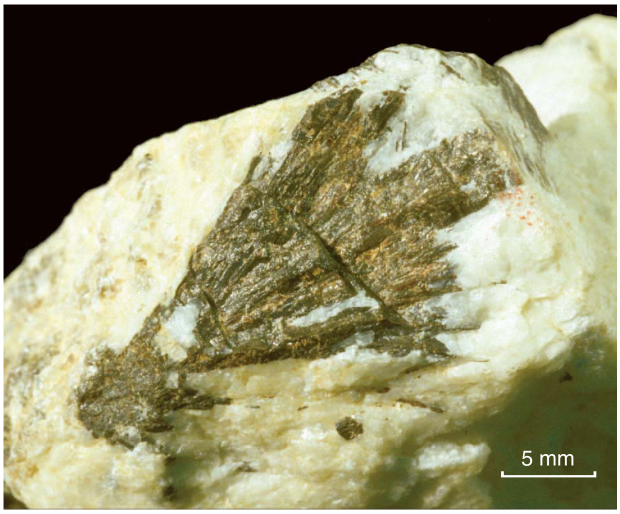

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Figure 4. Wodginite collected from its type locality at Wodgina (Simpson Collection, Western Australian Museum)

After the end of the Second World War, sporadic mining continued until the mid-1980s. From 1901 to 1985, tantalum concentrate (Ta_2O_5) produced mainly from alluvial and eluvial deposits around Wodgina totalled 231 t. Over the same period, hard-rock mining from small openpits and underground workings in the southern end of the Wodgina main-lode pegmatite produced 112 t of Ta_2O_5 (Hall, 1993).

In 1988 Pancontinental Mining commenced full-scale hard-rock mining of the Wodgina main-lode pegmatite and the Mount Cassiterite tantalum orebodies. The Wodgina main-lode pegmatite was worked out in 1994; however, the Mount Cassiterite operation continued to grow and became the world's second-biggest hard-rock tantalum mine, accounting for 7.25% of world production in 1997–98. The Wodgina operation was acquired by Sons of Gwalia in 1996. The company has since extended operations to the Mount Tinstone openpit and increased annual production to 680 t Ta_2O_5 in 2003.

In the South West region at Greenbushes, only small parcels of tantalite ore had been sold on an irregular basis prior to 1944. With the stimulation of demand as a result of wartime activities, tantalum production began on a regular basis. Dredge mining of placer deposits continued until the early 1970s when attention turned to the openpit mining of weathered pegmatites. The substantial increase in demand and associated price rises for tantalum in the early 1980s saw an increase in production from the weathered pegmatites, as well as an acceleration of a deep-drilling program to delineate the hard-rock tantalum orebody beneath the regolith cover. In 1990, with hard-rock openpit mining underway, the operations became part of Gwalia Consolidated Ltd, later to become Sons of Gwalia Ltd. Today, the Greenbushes operation is the largest hard-rock tantalum resource in the world, producing up to 560 t Ta_2O_5 per annum from the Cornwall pit. However, as a result of the downturn in the tantalum market in 2002, production at Greenbushes has been cut back to 340 tpa for 2003. At the same time, construction of the decline leading to a proposed underground tantalum mine beneath the Cornwall pit has been put on hold.

Sporadic tantalite mining also took place in many other areas of the State during the 20th century. These deposits were associated with tin and/or beryl or lithium-rich rare-metal pegmatites, but it was the alluvial and eluvial deposits associated with these pegmatites that generally attracted most attention from prospectors. However, there was some hard-rock mining, for example, at Tantalite Hill at Londonderry in the Coolgardie area. In the north, mining areas included the southeastern Kimberley around Mount Dockrell, and areas in the Pilbara region, especially Pilgangoora, Mount Francisco, Shaw River, and Moolyella. In the south, localities included Yinnietharra (Gascoyne region), Dalgaranga (Murchison area), Cattlin Creek near Ravensthorpe, Londonderry, and a number of prospects in the Kalgoorlie–Norseman region. Details of these and other mining operations have been given in Miles et al. (1945).

Two very different styles of tantalum mineralization, not related to pegmatites, were discovered in the early 1980s. Exploration between 1981 and 1984 discovered tantalum mineralization contained in regolith overlying the Mount Weld carbonatite near Laverton in the Eastern Goldfields. Investigations revealed that weathering of the original pyrochlore mineralization (Fig. 5) had resulted in the formation of a supergene ore zone comprising fine-grained phosphatic, clayey material containing total resources of about 145 Mt Ta_2O_5 (Duncan, 1990). In 1982, the Brockman polymetallic deposit was discovered in the Halls Creek area in the east Kimberley region. The deposit, hosted by an altered trachytic tuff, was estimated to have total resources of almost 50 Mt of extremely fine-grained polymetallic minerals, including tantalum-bearing columbite (Aztec Resources, 2001a).

The period 1997 to early 2001 saw an almost unprecedented increase in global demand for tantalum, largely due to a boom in the electronics industry, with a corresponding jump in demand for tantalum capacitors. Accordingly, prices for the metal increased rapidly, briefly reaching a peak of about A$670/kg in the first half of 2001. In Western Australia, the price stimulus caused a resurgence in tantalum exploration and mining. As a result, many of the old tantalum deposits and prospects in areas listed above were re-examined for possible economic tantalum occurrences using contemporary exploration techniques. In addition, many tailings dumps from old tin–tantalum workings in the same areas were investigated for possible economic recovery of tantalite.

In 2001, new tantalum mines were established at Bald Hill, south of Kalgoorlie, and at Dalgaranga in the Murchison region. Other tantalite prospects at Dalgaranga, as well as Binneringie (Bald Hill area), and Mount Deans (near Norseman), were re-evaluated and are currently subject to mining feasibility studies. Other highly prospective deposits that have been re-evaluated in recent years include the Arthur River alluvial deposits and hard-rock pegmatites near Yinnietharra, West Wodgina, Pilgangoora, and Mount Francisco in the Pilbara region, and Cattlin Creek on the south coast of Western Australia.

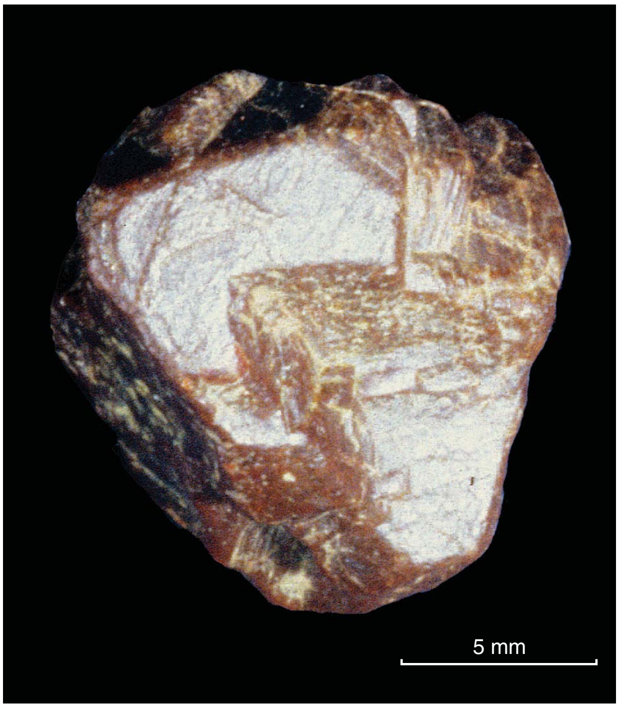

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Figure 5. The niobium–tantalum mineral pyrochlore. It is commonly associated with carbonatite, and peralkaline granite–syenite and metasomatite intrusions. Collected at Moolyella (Simpson Collection, Western Australian Museum)

Chapter 4

Mode of occurrence

Primary mineralization styles

Around the world, primary tantalum deposits have formed in a number of diverse geological environments and over a vast time span, from the late Archaean and Palaeoproterozoic pegmatites of Western Australia, Africa, Canada, and the Russian Federation, to the early Palaeozoic carbonatites of British Columbia, and the Cretaceous granites of Malaysia and Thailand.

Primary tantalum mineralization has five broad modes of occurrence, although it is the rare-metal pegmatites that are by far the dominant mineralization style. The five categories of primary tantalum mineralization styles are:

- Granitic rare-metal pegmatites;
- Rare-metal (Li–F) granites, also known as 'acidic granites' or 'apogranites'. An apogranite is an albitized and greisenized late-phase granite located at the peripheral and apical parts of earlier granitic intrusives, and commonly mineralized in rare elements such as Ta, Nb, Li, Rb, Be, Sn,W, and Mo;
- Peralkaline granites–syenites and metasomatites;
- Nepheline syenites;
- Carbonatites.

These five categories are summarized in Table 7 and further information relating to individual tantalum deposits around the world is available in Chapters 10–12. References to rare-metal (Li–F) granites and apogranites are given in Yin et al. (1995) and Raimbault et al. (1995).

Peralkaline granite–syenite and metasomatite, and nepheline-syenite mineralization styles and examples have been discussed in Sorensen (1974). Tantalum–niobium carbonatite deposits at Blue River, British Columbia have been described in McCrea (2001), and those at Mount Weld in Western Australia have been described in terms of mineralization style, geology, and geochemistry in Duncan (1990).

In Western Australia, granitic rare-metal pegmatites are almost exclusively the dominant style of primary tantalum mineralization, with the only exceptions being the carbonatite style at the Mount Weld deposit, and an unusual form of subalkaline granite–syenite mineralization at the Brockman deposit. These less common mineralization styles are discussed under their own subject headings in Chapter 12.

Granitic rare-metal pegmatites

Rare-metal pegmatites are present in many countries around the world. Although pegmatites range in age from Archaean to Cainozoic, most granitic rare-metal pegmatites containing significant rare-metal resources appear to have a close relationship with felsic granitic rocks of the late Archaean–Palaeoproterozic cratonic domains in Australia, Canada, Africa, South America, the Russian Federation, and India. These pegmatites may contain economic grades of the ores of tantalum, niobium, lithium, tin, beryllium, tungsten, rubidium, caesium, gallium, and hafnium. Other commodities present may include commercial-grade potash feldspar, albite and muscovite mica, and semi-precious stones such as tourmaline, topaz, garnet, zircon, beryl, and aquamarine. Emerald, the gem form of beryl, is also occasionally found in these rocks. Rare-metal pegmatites are associated with regional metamorphism that may vary from lower greenschist facies to anatectic grades (upper amphibolite to granulite facies; Sweetapple et al., 2001a).

In common with other pegmatites, rare-metal pegmatites generally have a dyke-like form, both horizontally and vertically, and are commonly only a few metres in thickness, and from a few metres up to 500 m in length. However, some pegmatites attain much larger proportions, such as the Greenbushes tin–tantalite–spodumene pegmatite in southwestern Western Australia. This huge pegmatite has mineralized dykes ranging from hundreds of metres up to several kilometres in length, and from tens to hundreds of metres in thickness (Partington et al., 1995).

The shape, size, attitude, and degree of fractionation of rare-metal pegmatites vary according to depth of emplacement, the competency of the host rock, and the prevailing metamorphic grade. At depth, in higher metamorphic-grade regimes, these pegmatites tend to form lenticular, ellipsoidal, and turnip-shaped bodies due to the ductility of the host rocks. Closer to the surface, they form a variety of flat-walled fracture fillings such as dykes, stocks, and tabular bodies by forcible emplacement into fissures in brittle country rocks. At the same time, the degree of fractionation and intensity of rare-element mineralization appears to increase towards the surface, and it is often the uppermost rare-metal pegmatites that contain the highest mineralized grades. In many cases, the shape and attitude of these pegmatites appear to influence the internal structure and the degree of fractionation and mineralization in these bodies. For example, tabular near-

Table 7. Genesis of economically significant tantalum mineral deposits

Primary mineralization styles

Granitic rare-metal pegmatites
Contain quartz, K-feldspar, a variety of lithium minerals (spodumene, petalite, and lepidolite), cassiterite, beryl, pollucite (a caesium mineral), and rubidium (as Rb-bearing muscovite, lepidolite, and microcline). This group represents the principal source of columbite–tantalite recovered mainly from large pegmatite deposits such as Greenbushes and Wodgina in Western Australia, Bernic Lake in Manitoba, and Nanping in southeast China. Other tantalum-bearing minerals in this group include wodginite, microlite, stibiotantalite, tapiolite, and strüverite

Rare-metal (Li–F) granites
Also known as ‘acidic granites’ or ‘apogranites’. Deposits are often strongly albitized or greisenized and commonly contain columbite–tantalite, microlite, strüverite, cassiterite, fluorite, amazonite, and lithium minerals (zinnwaldite, Li-muscovite, lepidolite, spodumene, and petalite). Principal columbite–tantalite deposits are located at Yichun in southeast China, Etykinskoye, Orlovskoye and Alakhinskoye in southern Siberia, and Beauvoir–Echassières in central France

Peralkaline granites–syenites and metasomatites
Host bodies (including pegmatites) form within alkaline granites and syenites, and volcanic equivalents such as trachyte, often with alteration zones (commonly brecciated), and may contain late-phase fluids rich in tantalum, niobium, lithium, and rare earth elements. Tantalum minerals include columbite–tantalite, pyrochlore, fergusonite, aeschynite, euxenite, polycrase, and samarksite. Principal deposits are located at the Ghurayyah deposit in Saudi Arabia, the Thor Lake Complex in the Northwest Territories of Canada, the Motzfeldt Complex in southern Greenland, and the Katuginskoye deposit in the Chita Province of southern Siberia

Nepheline syenites
Formed as zoned bodies within differentiated alkaline complexes. These rocks range from agpaitic nepheline syenites relatively high in sodium and potassium to the more aluminous, biotite-rich miaskitic nepheline syenites (Sorensen, 1974). Characteristic minerals include nepheline, microcline, albite, sodalite, analcime, alkali feldspar, plagioclase, aegirine, augite, nosean, and biotite. The Proterozoic Khibina and Lovozero Massifs in the Kola Peninsula of the Russian Federation are the world’s largest alkaline intrusions. At Lovozero, loparite is the principal ore mineral found in agpaitic nepheline syenites. Loparite is a source of rare earths, niobium, tantalum, and titanium

Carbonatites
Mineralization forms within carbonatites, which are usually subcircular pipe-like bodies up to 3–4 km in diameter, or may take the form of dykes, sills, small plugs, irregular masses, lava flows, and pyroclastic deposits. Host rocks include sovite, beforsite, and ferrocarbonatite. The tantalum mineral pyrochlore, and less commonly fergusonite and fersmite, occurs with bastnaesite, apatite, anatase, zircon, baddeleyite, magnetite, monazite, parisite, vermiculite, fluorite, and sulfide minerals. Apatite and crandallite are hosts to rare earth elements. Principal deposits include Mount Weld in Western Australia, the Niobec niobium mine in Quebec, and the tantalum-rich carbonatite deposits of southeast British Columbia

Secondary mineralization styles — regolith deposits

Deeply weathered deposits
Develop in areas of deep weathering (>50 m depth) over host bedrock. Particularly relates to deep weathering in situ of granitic rare-metal pegmatites where the primary pegmatite has been almost completely altered to kaolin with remnant quartz. The weathered zone contains resistate minerals such as cassiterite, columbite–tantalite, and strüverite. Prior to mining, a deposit of this type was present at Greenbushes in a 30–50 m deeply weathered kaolinitic profile overlying the host pegmatite

Placer deposits
Form as eluvial, colluvial, alluvial, and marine placer deposits. Deposits are derived from the weathering of rare-metal pegmatites and/or rare-metal K-feldspar granites. The world’s largest tin placer (cassiterite) deposits extend over 2300 km along the peninsula through Malaysia, Thailand, and Burma. Deposits contain substantial quantities of tantalite–columbite, strüverite, and other tantalum minerals. There are many extensive marine placer deposits situated along the coastlines of these countries. Other locations for tin and tantalite placer deposits include the Pilbara and Greenbushes areas of Western Australia, Pitinga in Brazil, and many countries in central Africa, particularly the Democratic Republic of the Congo

SOURCE: Cerny and Ercit (1989)

horizontal to shallow-dipping rare-metal pegmatites appear to be the most fractionated and best mineralized (Cerny, 1993a,b). A schematic sketch of a concentrically zoned rare-metal pegmatite is shown in Figure 6.

Around the world there are exceptions to this model, including Western Australia’s very large Greenbushes pegmatite. This deposit contains high-grade tantalum mineralization in steeply dipping, asymmetric pegmatite dykes. However, the proposed model appears to apply to other major Western Australian tantalum deposits such as the Mount Cassiterite orebody at the Wodgina deposit in the Pilbara region, where 5–80 m-thick stacked tantalum-bearing pegmatite sheets dip 15–25°. At the Bald Hill mine south of Kalgoorlie, shallow-dipping, near-tabular pegmatite bodies are currently being mined for high-grade tantalite.

According to Cerny (1993b), the distance of a rare-metal pegmatite type from its host granite is proportional to the thermal stability of the pegmatite’s particular melt composition. This appears to be the main reason for the regional zonation of rare-metal pegmatites (Fig. 7). Accordingly, melts having low viscosity and high mobility migrate further down the regional thermal gradient as they travel outwards from the parent granite. Rare-metal pegmatites that have migrated to the outermost regional aureoles tend to be the most fractionated, the most complex in their internal structure and paragenesis, and are more extensively mineralized and replaced, especially with respect to tantalum, niobium, lithium, and beryllium. Conversely, comparatively simple pegmatites such as the beryl type are generally restricted to the intermediate regional aureoles.

Cerny (1989a, 1993a) proposed a classification for tantalum-bearing rare-element pegmatite deposits. This classification comprises four principal types: beryl (with beryl–columbite and beryl–columbite–phosphate subtypes); complex (with spodumene, petalite, lepidolite, and amblygonite subtypes); albite–spodumene; and albite. An outline of Cerny's classification is given below and is also listed with additional data in Table 8.

Beryl type

The beryl type represents a relatively simple form of rare-element pegmatite. This type is typically emplaced close to the margins of the comagmatic host granite (Fig. 7), and adopts a fracture-filling tabular or lenticular to bulbous form. Zonation comprises an aplitic, granitic, or muscovite-rich border zone, a wall zone of graphic K-feldspar and quartz, and a quartz core with a marginal zone of blocky K-feldspar with or without pods and layers of saccharoidal albite and cleavelandite. Ferromagnoan phosphates are sometimes associated with the albite. A simple mineralogy of tantalum and niobium oxide minerals (mainly columbite–tantalite and ixiolite), together with coarse muscovite and beryl, garnet, or tourmaline, is associated with the albite-rich units.

In Western Australia, the Yinnietharra pegmatite field (including the Arthur River deposit) in the Gascoyne River region belongs to the beryl type (Sweetapple, 2000).

Complex types

Spodumene, petalite, and amblygonite subtypes

These complex rare-element pegmatites comprise the zoned lithium-rich subtypes containing aluminosilicates and/or lithium–aluminium phosphates. Each of these

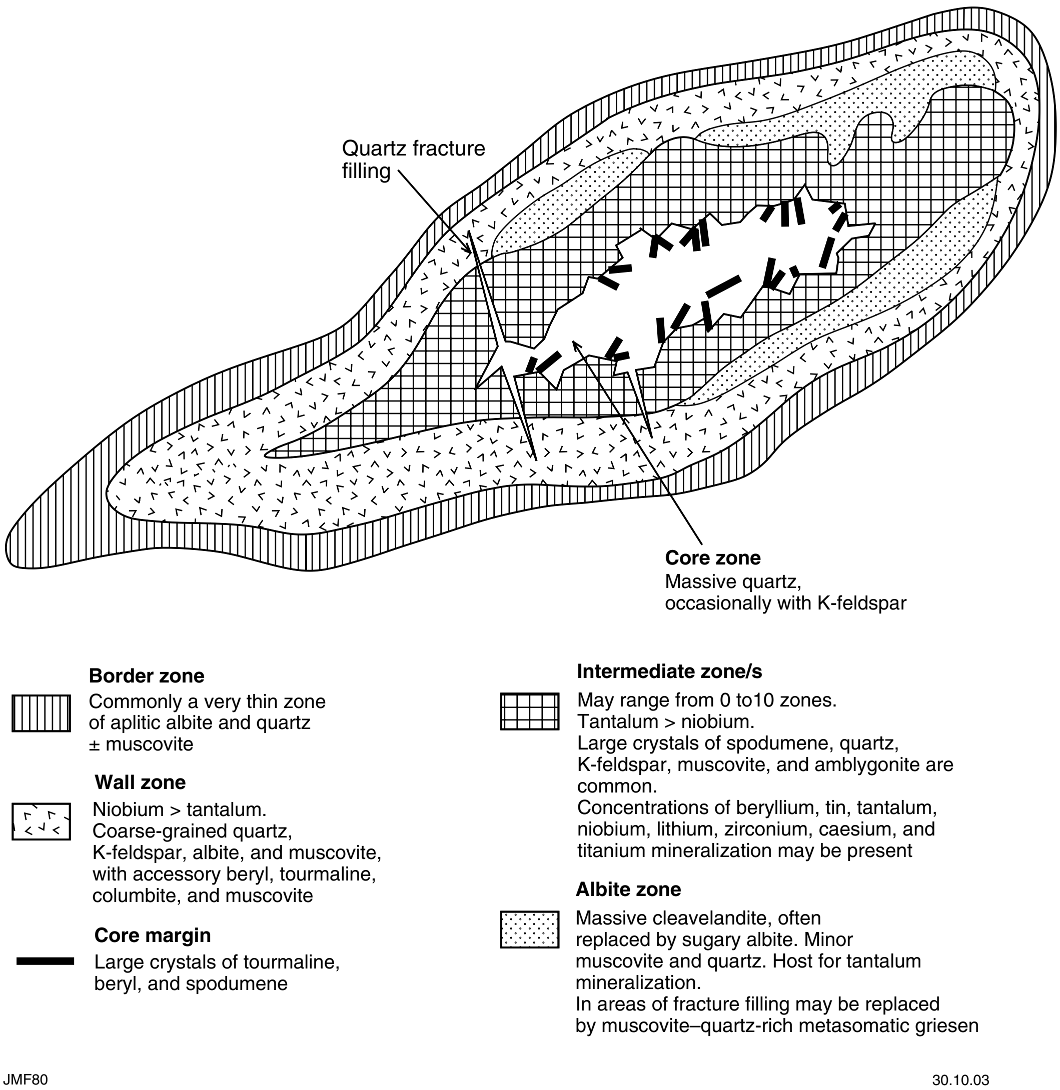

Figure 6. Schematic cross section of a concentrically zoned rare-metal pegmatite (modified from Cerny, 1993a)

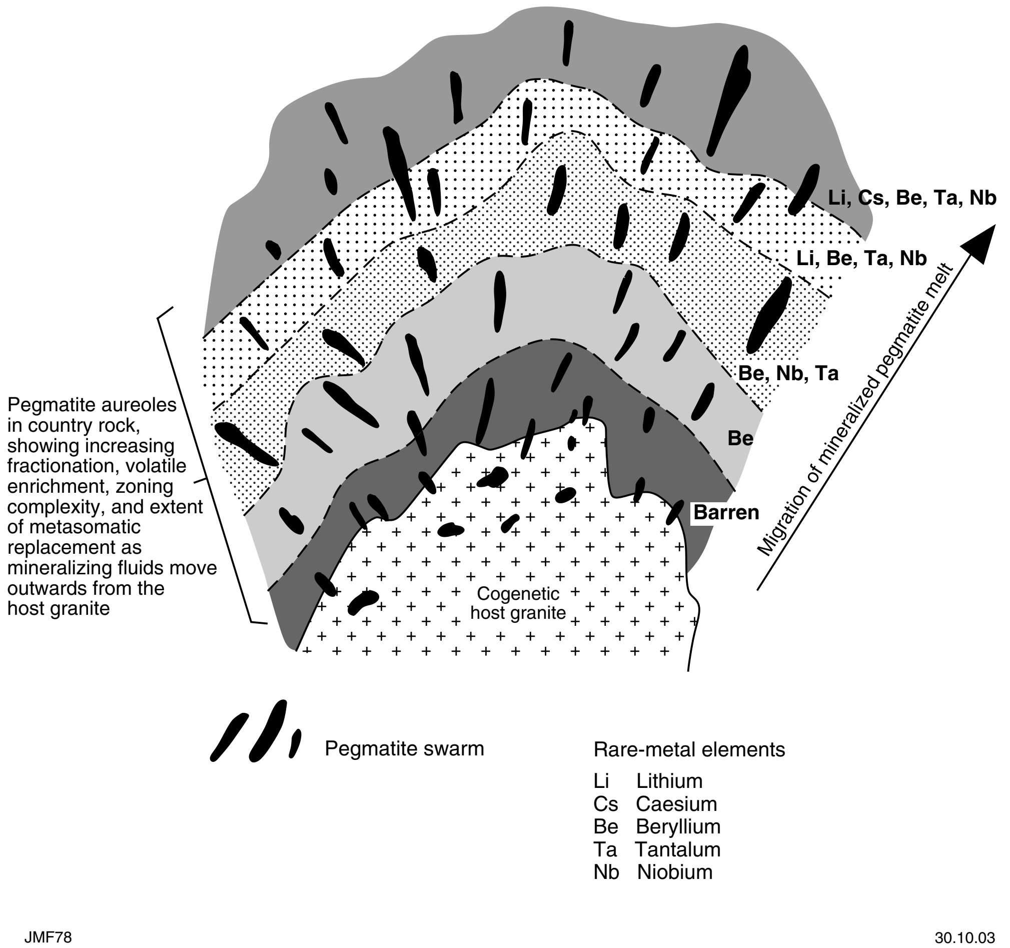

Figure 7. Schematic representation of regional rare-metal pegmatite zoning (modified from Cerny, 1993b)

subtypes is defined according to its dominant lithium mineral-bearing phase and they represent the most complex style of fractionation in terms of geochemistry and internal structure of all the rare-element pegmatites. They are generally found in the outer margins of the regionally zoned comagmatic rare-element pegmatite swarms (Fig. 7).

Their complex internal structure may be made up of 6–12 discrete zones of primary (dominant phase) and secondary replacement units. The structure of the zones is generally concentric, but may also be asymmetric or disrupted by layered units. In these types, the border zone is generally absent; however, the diversely zoned interior may contain extensive zones of platy or saccharoidal albite, as well as secondary zones of muscovite or lithium micas. A number of internal zones may contain giant crystals of quartz, K-feldspar, and lithium-bearing minerals. Occasionally, K-feldspar may also be incorporated in the quartz core.

Tantalum mineralization may be incorporated in three internal host units:

- cleavelandite or saccharoidal albite
- secondary muscovite replacing rich K-feldspar zones
- primary or secondary lithium micas.

Due to the steep fractionation gradients between the outer and inner zones of these subtypes, the tantalum mineralogy is complex and highly diversified, with six to eight tantalum minerals commonly present and this may reach a maximum of 14 tantalum minerals in some deposits. The complex tantalum mineralization is controlled by the ratios of Nb/Ta, Fe/Mn, Ti/Ta, and Sn/Ta, together with the presence of fluorine in the various zones and replacement units. Minerals may include columbite–tantalite, microlite, ixiolite, wodginite, and cassiterite, and less commonly tapiolite, stibiotantalite, simpsonite, and other tantalum minerals.

The Tantalum Mining Corp. of Canada Limited (TANCO) rare-metal pegmatite deposit in Manitoba, Canada is representative of the complex petalite subtype. The TANCO pegmatite is a highly fractionated pollucite-bearing variety that contains numerous tantalum oxide minerals.

In Western Australia, the Greenbushes tin–tantalum–spodumene deposit is a member of the complex spodumene subtype. The Greenbushes orebody comprises four main layered pegmatite units without a classic zonation pattern. The ore is mainly tantalite, tantalite-enriched cassiterite, stibiotantalite, and minor tantalum minerals

Table 8. Classification of tantalum-bearing rare-element pegmatites

Type	*Subtype*	*Mineral assemblage*	*Economic potential*	*Ta/Nb ratio*	*Typical size (tonnes Ta)*
Beryl	Beryl–columbite	Beryl, columbite–tantalite	Beryllium, (niobium–tantalum)	0.91 – 3.33	≤2 000
	Beryl–columbite–phosphate	Beryl, columbite–tantalite, phosphate minerals	Beryllium, (niobium–tantalum)	0.91 – 3.33	≤2 000
Complex	Spodumene	Spodumene, beryl, tantalite, (amblygonite, lepidolite, pollucite)	Lithium, rubidium, caesium, beryllium, tantalum, (tin, gallium, hafnium)	1.25 – 8.33	>5 500
	Petalite	Petalite, beryl, tantalite, (amblygonite, lepidolite)	Lithium, rubidium, caesium, beryllium, tantalum, (tin, gallium, hafnium)	1.25 – 8.33	>5 500
	Lepidolite	Lepidolite, topaz, beryl, microlite, (pollucite)	Lithium, rubidium, caesium, tantalum, beryllium, (tin, gallium)	1.67 – 5.00	≤2 000
	Amblygonite	Amblygonite, beryl, tantalite, (lepidolite, pollucite)	Lithium, rubidium, caesium, tantalum, beryllium, (tin, gallium)	1.25 – 8.33	>5 500
Albite–spodumene		Spodumene, (cassiterite, beryl, tantalite)	Lithium, tin, (beryllium, tantalum)	0.83 – 2.00	≤10 000
Albite		Tantalite, beryl, (cassiterite)	Tantalum, (tin)	0.83 – 1.25	<10 000

SOURCE: Cerny (1989a, 1993a)

NOTE: ( ) denote minerals that are not always present and subordinate economic potential such as wodginite, tapiolite, and microlite, as well as a major discrete spodumene resource. The petalite subtype is represented in Western Australia by the Tantalite Hill pegmatite at Londonderry in the Coolgardie district, and the amblygonite subtype is represented by the Binneringie pegmatite located south of Kalgoorlie (Sweetapple, 2000).

Lepidolite subtype

The lepidolite subtype is distinctly different from the other three complex types, being rich in fluorine, which has a tendency to destabilize lithium aluminosilicate minerals, and deficient in phosphorus. These rare-metal pegmatites are characterized by the low viscosity and high mobility of their fluorine- (and occasionally boron-) enriched melts. For this reason, they are commonly located on the outer edge of the zoned pegmatite groups (Fig. 7). On average, individual lepidolite pegmatites are often small in size, tending to form swarms of small lenticular and tabular bodies.

These pegmatites also exhibit a strong zonation pattern, but have a variable and somewhat irregular internal structure. Since the supply of lithium is relatively restricted, mineralized pods containing lepidolite develop only in the centre of the zoned structure. Fine-grained units containing lepidolite with or without albite are host to tantalum mineralization, usually tantalum-rich microlite and cassiterite, and minor manganocolumbite. Topaz and beryl may also be present.

Albite–spodumene type

This type of rare-metal pegmatite tends to form discrete sub-parallel swarms. Individual pegmatites may form tabular bodies up to 3 km in length and 60 m in width. They may also exhibit a consistent downdip length of up to 1000 m. Zoning is often simple or even non-existent. When present, zoning may consist of a thin wall zone of fine-grained quartz and albite, followed by an intermediate zone of medium-grained albite and quartz with or without mica, with huge subparallel crystals of spodumene and lesser amounts of K-feldspar. Sometimes a core zone of blocky K-feldspar with or without minor quartz may be present.

These pegmatites generally contain the highest concentration of lithium-rich mineralization of all the rare-metal pegmatites. Accordingly, columbite–tantalite, cassiterite, and K-feldspar are dispersed within the spodumene-rich zone, whereas beryl is concentrated in K-feldspar-rich dykes.

The Mount Cassiterite rare-metal pegmatite located at the Wodgina tantalum deposit in the Pilbara region of Western Australia is an example of this type (Sweetapple et al., 2001b).

Albite type

This rare-element pegmatite type is comparatively uncommon, as they usually occur as individual dykes within complex-type pegmatite swarms or occasionally form groups of their own. These pegmatites generally form small intrusions up to a few hundred metres in length and less than 5 m thick, and may range from subvertical to subhorizontal in attitude. Zoning may or may not be present. However, when present, zoning may be well developed with a border zone of fine-grained quartz and albite. This is followed by an albitic wall zone comprising cleavelandite, often found in the hangingwall, and saccharoidal albite, often located in the footwall. The core area is filled with lenses of quartz and blocky K-feldspar that may be coated with fine- to medium-grained muscovite.

In the albite type, relatively simple tantalum mineralization is dispersed throughout the albitic zones and the muscovite core margin. The main minerals are columbite–tantalite, and tantalum-rich rutile and cassiterite, with occasional minor microlite and euxenite. Beryl is a common accessory mineral that is found separately in the blocky K-feldspar units. The main-lode pegmatite units of the Wodgina tantalite orebody at the Wodgina deposit in the Pilbara region are representative of the albite type (Sweetapple et al., 2001b).

Secondary mineralization styles

Regolith deposits

Deeply weathered deposits

Deeply weathered tantalum deposits are normally located in situ over a primary tantalum source located at depth. In the majority of cases, these deposits have been subjected to deep weathering processes for long periods. For example, in Western Australia virtually all near-surface rocks have been affected to some degree by deep weathering processes since the end of the Permian, and in some areas lateritic profiles have developed to a depth of at least 60 m (Fetherston, 2002). Other areas of ancient landscapes where deep weathering is evident include many parts of Africa (e.g. Ethiopia, Mozambique, Uganda, and Zimbabwe), western coastal Malaysia and Thailand, and over much of eastern Australia, especially in the north of the continent. Deeply weathered terrains are commonly not present in high-latitude northern hemisphere countries such as Canada and the Russian Federation where ice-scouring events over the last several million years have for the most part removed any evidence of former deep-weathering profiles.

In Western Australia, there are numerous examples of economic grades of mineral ores recovered from the regolith. Deep weathering processes in the regolith horizon may form much higher concentrations of minerals resistant to the effects of weathering when compared to grades contained in the underlying unweathered host rock. This is an important process for the formation of enriched tantalum-regolith deposits at a number of localities in the State.

The Mount Weld carbonatite rare earths–tantalum–niobium–phosphate deposit, located approximately

240 km north-northeast of Kalgoorlie, is an excellent example of this process. At this deposit, a regolith horizon up to 70 m thick has developed over the primary carbonatite pipe. The upper part of this regolith consists of a supergene zone comprising discrete enriched deposits of rare earths and tantalum–niobium mineralization. In this deposit, deep weathering processes have formed a suite of sediments and palaeosols with a complex secondary mineralogy in which tantalum and niobium ions have been concentrated in the phosphate mineral crandallite, in the form of pseudomorphs after pyrochlore (Duncan, 1990). Work to date suggests that minerals contained within the primary carbonatite have concentrations too low for economic recovery.

At Greenbushes in southwestern Western Australia, commencing in the early 1970s, large quantities of tin and tantalite were mined for almost 20 years from a 30–50 m deeply weathered horizon of kaolinized pegmatite overlying the massive Greenbushes primary pegmatite tin–tantalum orebody.

In the Pilbara region of the State, mining operations are currently in progress at the Mount Cassiterite and Mount Tinstone orebodies that form part of the Wodgina tantalum deposit. In these orebodies, mining is comparitively easy due to the highly weathered nature of the mineralized rare-metal pegmatites and the surrounding greenstone host rocks. It is estimated that deep weathering of the pegmatites extends downwards from the surface for a minimum of 60 m. In these deposits, very fine grained tantalite is contained within white, highly kaolinized material largely derived from the weathering of feldspars. Angular quartz particles are the only visible unweathered crystalline material remaining from the original pegmatite (Fig. 8).

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Figure 8. Highly kaolinized tantalum ore at Wodgina that has been derived from deep weathering of feldspar in pegmatites in the Mount Tinstone orebody

Deeply weathered deposits are summarized in Table 7 and further information is available on a number of deeply weathered tantalum deposits in Chapters 10–12.

Placer deposits

There are substantial tantalum placer deposits located around the world. These deposits commonly occur in association with tin, and result from chemical and mechanical weathering processes effecting the breakdown of rare-metal pegmatite and acidic granite host rocks. Close to the host pegmatite, eluvial deposits may develop, followed by colluvial mantles in the form of outwash fans and scree deposits at the base of slopes. The weathering process is continued with the formation of alluvial placers in stream and river channels, and finally as reworked sediments in offshore marine placers. Placer deposits are summarized in Table 7 and further information is available in Chapters 10–12.

Eluvial deposits and colluvial mantles

Tantalite deposits are often concentrated in eluvial deposits formed immediately downslope of the host pegmatite by mass-wasting processes, and may consist of rock scree, surficial detritus, and residual soils enriched with tantalum minerals from sheetwash and eolian processes. In Western Australia, many tantalite eluvial deposits have been mined in the Murchison and Pilbara regions, especially in the Wodgina, Moolyella, and Tabba Tabba – Strelley areas. These eluvial deposits have largely been worked out.

Mineralized colluvial mantles may form as unconsolidated soils or outwash fans of sand, gravel, and rock fragments at the break of slope of hills containing tantalum-bearing pegmatites. Colluvial deposits are found in many localities in western coastal Malaysia and Thailand, and extending into Burma.

Alluvial placers

Alluvial placers constitute the most common form of tantalite placer deposits. Due to tantalite's high specific gravity of 8.1 (maximum), deposits capable of being mined are concentrated as stream-channel sediments in a mixture of clay, mud, sand, and gravel. These placers are found in many countries in Africa, especially in the Democratic Republic of Congo where there are extensive areas of thick alluvial sediments containing rich concentrations of tantalite. Extensive tantalite placer deposits are also present in Brazil, Guyana, and Bolivia in South America. In many of these areas in Africa and South America, tantalite is recovered by artisanal mining operations.

Alluvial placer deposits are also present within a linear zone that continues for approximately 1500 km along the coastal plain of western Malaysia, extending northwards from Melaka to Georgetown and continuing from Phuket in Thailand almost to Rangoon in Burma. In this area, resistate minerals such as cassiterite, columbite–tantalite, and strüverite are recovered largely by dredge mining operations.

In Australia, there are numerous smaller tantalite placer deposits in stream-channel sediments located in old tin-mining areas in the northwestern Northern Territory, northern Queensland, Victoria, and in the Murchison, Pilbara, and Greenbushes areas of Western Australia.

The classification of alluvial placer deposits for the Shaw River tin field in the Pilbara region has been discussed by Sweetapple (2000). Over the last 100 years, a substantial amount of tin–tantalum minerals have been recovered from alluvial placer deposits and prospects in this area. Up until 1975, the Shaw River tin field produced 6585 t of tin and 548 t of tantalite concentrates (containing 20.2 t of Ta_2O_5), with the greatest production from alluvial placer deposits (Blockley, 1980). Many of these production sites are listed in Chapter 12 and their locations are shown on Plate 1. The following description of the five main alluvial tin–tantalum environments from the region may provide a useful model for the location of tin–tantalum placers, both in the wider Pilbara region and also in other areas around Arthur River – Beryl Hill in the Capricorn Orogen, Mount Heartbreak in the Halls Creek Orogen, and Greenbushes in the Yilgarn Craton (Plate 1).

Major creeks

Major creeks are usually tributaries of major river systems. Alluvial deposits are channel and bar sequences comprising unconsolidated sands and gravels. Creek workings in the Shaw River tin field have typically been over several hundred metres of a 10–15 m-wide stream channel. Occasionally some workings have extended for over 6 km and have been up to 90 m in width. The highest grade tin–tantalum mineralization is contained in a hard, basal, medium-grained clayey sand to gravel unit varying from 0.1 to 1.5 m in thickness. This unit is overlain by up to 3.0 m of sandy to gritty loam, sometimes with a clay matrix that contains low- to moderate-grade mineralization. The overburden consists of 0.5 – 1.5 m of medium- to coarse-grained sand and minor silt containing occasional lenses of low-grade mineralization in sandy fractions.

Deep leads

Deep leads are concealed palaeodrainage channels related to major creek systems that are situated some distance away from present stream centres. These channels are buried by up to 2 m of alluvial overburden and are reported to contain high-grade mineralization up to 2 m thick and 10–60 m wide. This type of deposit represents an important potential tin–tantalum resource in the Shaw River alluvial area, and possibly in the Moolyella area (Plate 1).

Tertiary gravels

Of probable early Tertiary age, these gravels are likely to represent the oldest Cainozoic sedimentary unit. They consist of poorly sorted, polymict pebble beds in a loam, clay, or carbonate matrix. The unit ranges from 1 to 4 m in thickness and the lowermost portion of the unit (<30 cm thick) generally contains the mineralized horizon. Tertiary gravel deposits occur at Coondina and Cooglegong Creek (Plate 1), and at the Friendly Creek tin deposits that are also known as the Yule River tin deposits (Lat. 21°14'30"S, Long. 118°19'26"E; Blockley, 1980)

Small incised creeks

These deposits are present in the headwater catchments of major creeks. Creeks that are sharply incised may contain small quantities of high-grade alluvial mineralization. In headwater catchments of the Shaw River tin field, creeks associated with quartz monzonite or greenstone lithologies are typical of this type of deposit. Alternatively, shallowly incised creeks appear to contain only small to moderate quantities of typically low-grade mineralization. McCarthy's Creek at the Wodgina mine is an example of this type.

Other sources

Many tailings dumps from previously mined alluvial deposits have been reworked to trap previously unrecovered tin–tantalum alluvial ore using superior recovery techniques. Ore-grade material recovered from these deposits is extremely variable. Monsoonal rains may also cause annual flooding that results in the recharge of small deposits of tin–tantalum minerals eroded from upstream alluvial and eluvial deposits, and tailings dumps.

Marine placers

Marine tin–tantalum placers have been concentrated by current and wave action in reworked offshore marine sediments in places off the coast of western Malaysia, Thailand, and Burma. Dredge mining is employed to recover the ore.

Chapter 5

Exploration for tantalum in Western Australia

This chapter examines exploration techniques and the potential for the discovery of new deposits of primary and secondary tantalum in Western Australia. Currently, most tantalum deposits in the State are either sourced from columbite–tantalite and related tantalum mineralization in granitic rare-metal pegmatites or from secondary placer deposits developed from weathering of primary pegmatite deposits. Tantalum mineralization related to carbonatite and subalkaline syenite deposits of rare earths (similar to Mount Weld and Brockman respectively) are not discussed here, as these deposits appear to be the exception rather than the rule, and the technology for economic extraction of tantalum from these deposits is still in the developmental stage.

At present, it would appear that almost all significant surface expressions of rare-metal pegmatites in the State have been discovered and utilized for their tantalum and other rare-mineral resources. It is now necessary to develop techniques to assist exploration geologists to locate hitherto 'blind' rare-metal tantalite deposits. Likewise, most tantalum secondary deposits have also been largely worked out and it is likely that the discovery of new rare-metal tantalum pegmatites may also result in the discovery of related regolith deposits in situ, and placer deposits in buried palaeochannels.

Background research

As with any well-managed exploration program, the first stage is to establish the prospectivity for potential tantalum-bearing granitic rare-metal pegmatites in various areas of the State. The Geological Survey of Western Australia within the Department of Industry and Resources provides many services to assist the mineral industry in relation to historical mining data, mineral statistics, and mineral tenements, as well as the provision of geological maps and publications, mineral prospectivity packages, and access to previous mineral exploration reports.

The Department's website at <http://www.doir.wa.gov.au> provides on-line access to nine Statewide databases to assist with planning an exploration program. The first of these is Mineral Titles On-line (MTO), a tenement information system providing details on mineral tenement status, location, and ownership. Complementing this database is the TENGRAPH system that graphically depicts the position of mining tenements in relation to other land information and provides details on tenements, land tenure, and topography.

Access to geoscience data is available in seven databases covering the State's geology, mineral resources, geochemical, and geophysical surveys. Graphical data from many geoscience datasets in an active GIS environment may be browsed using GeoVIEW.WA. In the search for minerals such as tantalum, the Department's mines and mineral deposits information (MINEDEX), and Western Australian mineral exploration (WAMEX) databases are useful tools.

The MINEDEX database provides detailed information on mining projects and sites, including project ownership, percentage owned, mineral commodity group, site coordinates, mine operating status, estimated mineral resources, notices of intent, and mine operators and addresses.

Access to open-file company mineral-exploration reports is available on the WAMEX database. This database provides a search capability on map names or index numbers, tectonic units, target commodities, assays, geoscience keywords, exploration companies, and tenement types. Each record of a mineral exploration program contains an annotation for an exploration program that may include geochemical sampling, geophysical surveys, assays, geological mapping and interpretation, and resource evaluation. Copies of complete open-file exploration reports are available for viewing at the Department's head office in Perth and at the Kalgoorlie regional office. Recent reports in digital format are now available for online viewing. As far as mineral exploration for tantalum is concerned, currently there are about 100 open-file mineral exploration programs reported in WAMEX.

Summary of exploration techniques

Age of primary deposits

As previously noted, the majority of mineralized granitic rare-metal pegmatites around the world appear to have a close relationship with felsic granites that formed in late Archaean–Palaeoproterozoic cratonic domains. In Western Australia this association is recognized in the Pilbara Craton, with the rare-metal pegmatites being related to the 'younger' granite suite of 2.89 – 2.83 Ga age that intruded both the greenstones and the older granitoid suite (Sweetapple et al., 2001a). In the southwest of the State, the massive late Archaean Greenbushes pegmatite, which intrudes amphibolites and metasedimentary rocks, has been dated at 2.53 Ga (Partington et al., 1995). Sweetapple (2000) noted that the younger Pilbara late Archaean granites often have distinctive geochemical signatures. If it were possible to recognize geochemical signatures relating to particular late Archaean granites in the field, then it would perhaps be useful to target regional rare-metal pegmatite exploration in Archaean greenstone sequences in close proximity to these younger granites. This is of particular significance in Archaean mafic to ultramafic and metasedimentary units where pegmatites may occur in sheeted swarms or stockworks (Nisbet, 1984).

Regional controls affecting the distribution of pegmatites

In the Pilbara region of Western Australia, it is estimated that 63% of all rare-metal pegmatites are located within greenstones no more than 5–10 km distant from their parent granite and are also in close proximity with regional lineaments. Fifty-three percent of these pegmatites are within mafic–ultramafic metavolcanic greenstone lithologies, a factor worth considering as these lithologies make up only about 20% of the granite–greenstone terrane. Similar relationships have also been observed in the mafic–ultramafic host rocks both in the Yilgarn Craton of southern Western Australia and in the Archaean Superior Province in Canada (Sweetapple et al., 2001a).

Geophysical signatures and structural controls

From a regional perspective, pegmatite bodies are normally quite unresponsive to airborne magnetic surveys. By contrast, gravity and radiometric surveys, particularly low-level or ground surveys, may be of use in detecting blind pegmatite bodies, provided there is sufficient difference in rock density, or in radiometric uranium, thorium, or potassium anomalies between the pegmatite and host rocks. However, in areas of known pegmatite swarms, magnetic surveys may be used to detect zones of crustal weakness such as major faults, shear zones, or abrupt changes in lithology that may have been exploited as conduits by mineralized pegmatite melts migrating out from their host granites (Fig. 9).

Partington et al. (1995) suggested that in the case of the giant Greenbushes tantalum–tin–lithium pegmatite in the southwest of the State, the pegmatite swarm was intruded synchronously with movements along the Donnybrook–Bridgetown shear zone at about 2.53 Ga and was emplaced parallel to the shear direction. In the Pilbara region, Sweetapple et al. (2001a) estimated that 54% of all pegmatites are affiliated with major and associated second-order fault structures related to internal craton boundaries. Away from these structures, there is a marked decline in the number of pegmatites. In the Superior

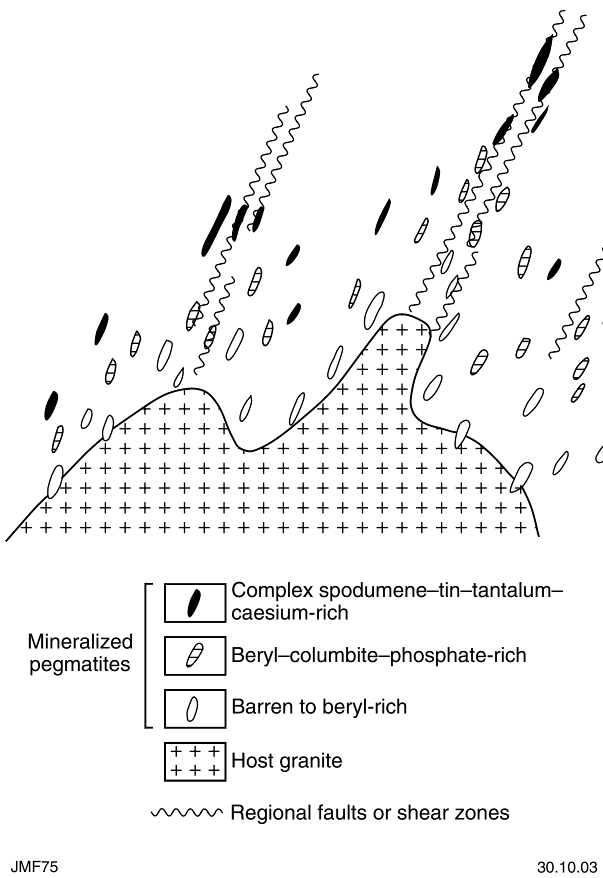

Figure 9. Schematic section showing upward migration of highly fluid pegmatite melts from the parent granite along regional structural shears and faults (modified from Cerny, 1989b)

Province in Canada, a similar spatial situation exists between rare-metal pegmatites and internal craton boundaries.

Regional rare-metal pegmatite zoning and lithogeochemical anomalies

Recognition of younger granitoid bodies adjacent to a local pegmatite swarm is not always possible, as the granitic rocks may have no surface expression. However, if a relationship between pegmatites and a host granite is established, exploration for rare-metal zonation patterns in the local rare-metal pegmatites may be carried out based on the work of Cerny (1993b). Cerny recognized that rare-metal pegmatites tend to become increasingly fractionated, together with the accumulation of higher concentrations of rare elements (particularly tantalum, niobium, and lithium) with increasing distance from the host granite (Fig. 7). In experimental models, Baker (1998) estimated that the maximum distance between the Pilbara 'younger' host granites concealed at depth and related rare-metal pegmatites was no more than 5 km, and their surface separation was generally less than 10 km.

Lithogeochemical haloes are probably the most successful method for the detection of concealed rare-metal pegmatites. In general, these haloes may be matched to the increasing fractionation and concentration of rare-earth elements mentioned above. For example, Cerny (1989b) identified boron, lithium, tin, and beryllium as diagnostic elements for beryl–columbite pegmatites, and boron, lithium, tin, caesium, beryllium, and rubidium as diagnostic elements for tantalum-enriched pegmatites with a high Ta:Nb ratio. In some cases, dispersion haloes of these elements may be found in host rocks hundreds of metres from the blind pegmatite (Nisbet, 1984). However, it must be remembered that various elements have different degrees of mobility and may be detectable at different distances from the target pegmatite. If this factor is taken into consideration, together with background values in local host rocks, the detection of multi-element haloes becomes possible and may lead to the discovery of a new rare-metal pegmatite. An example of lithogeochemical haloes overlying the TANCO tantalum orebody is shown in Figure 10.

In the area around Pilgangoora in Western Australia's Pilbara region, regional zoning has been defined within the Archaean Warrawoona Group greenstones surrounding granites of the late Archaean Carlindie Batholith. Close to the greenstone–granite contact, simple quartz–microcline–muscovite pegmatites are present that contain only low levels of tantalum, rubidium, caesium and lithium, with low Ta:Nb ratios. Two kilometres from the contact, large, poorly to moderately zoned spodumene–quartz–albite pegmatites are present in mafic to ultramafic greenstones. These spodumene-rich pegmatites are enriched in tantalum, lithium, rubidium, and caesium, and have high Ta:Nb ratios. Anomalous lithium, caesium, and rubidium lithogeochemical haloes were detectable at up to 80 m from these pegmatites (Nisbet, 1984).

Secondary dispersion haloes in regolith materials

The presence of pegmatites concealed beneath thick, deeply weathered lateritic or duricrusted profiles may be detected by the presence of weaker secondary dispersion haloes either in the deeply weathered rock material or in the overlying soils or other unconsolidated material. Most of these elements are sourced from the breakdown of minerals from the primary deposit into the regolith environment. In these areas, the development of discriminant-function analysis models designed to suit the particular environment may be useful in discriminating between regolith materials formed over mineralized and unmineralized pegmatites, and country rocks.

A significant secondary dispersion halo has been identified over the Greenbushes deposit. A large dispersion halo of tin, arsenic, and beryllium, together with smaller amounts of antimony, niobium, tantalum, boron, and lithium, is present in the regolith over an area of up to 20 × 10 km covering areas of primary mineralization (Smith et al., 1987).

Prospecting rare-metal pegmatites for tantalum

The location of a rare-metal pegmatite with a lithogeochemical signature indicating the likely presence of tantalum may set in place an exploration strategy involving a number of techniques, some of which are unique to tantalum-rich pegmatites. The following is a brief summary of the main issues relating to the exploration phase.

Pegmatite dimensions and structure

The only guide to the likely alignment and size of a partially subsurface pegmatite may be indications of quartz float on the surface. However, if the pegmatite is almost completely beneath the surface, the geophysical methods mentioned above may be useful in certain circumstances in providing information about the body's structure and size. Since geophysical methods cannot always be used, and bearing in mind that many pegmatites are thin dyke-shaped bodies, the only really successful method is to carry out a series of close-spaced drilling traverses to determine the body's subsurface trend, linear extent, shape, thickness, and attitude.

Most pegmatites are less than 500 m in length, a few metres in thickness, and may vary in shape from linear or branching dykes to stocks, tabular, lenticular, ellipsoidal, and even turnip-shaped bodies. Pegmatites are commonly found as multiple stacked bodies comprising around three or more tabular pegmatite sheets that may occur in a variety of attitudes from flat-lying to vertical.

It is worth noting that Cerny (1993a,b) considered tabular pegmatites ranging from flat-lying to shallow dipping to be the most fractionated and best mineralized. However, in the case of the steeply dipping Greenbushes deposit it is clear that this observation does not always apply.

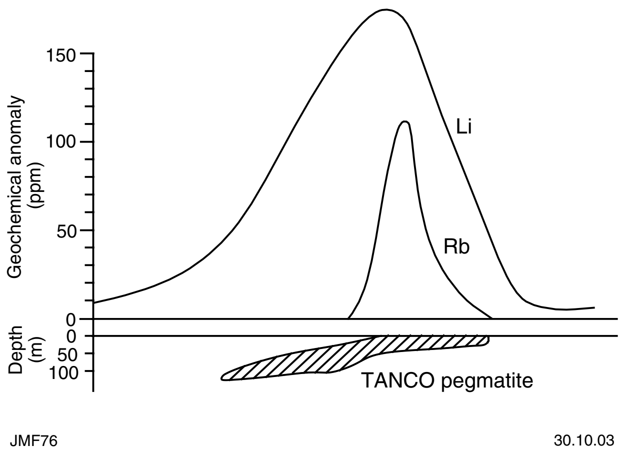

Figure 10. Lithium and rubidium geochemical anomalies in greenstones overlying the TANCO tantalum deposit, southeastern Manitoba (modified from Cerny, 1989b)

Zonation and geochemical sampling

Rare-metal pegmatites typically display at least two internal zones including the quartz core and the wall zone with replacement units. Sometimes complex tertiary intermediate zoning may also be present, as detailed in the zoning classification proposed by Cerny (1993a). Complex tantalum-rich pegmatites may include up to ten or more distinct mineralized zones (Fig. 6). It is important to remember that many mineralized pegmatites (typically simple pegmatites) may show only a partial amount, or even none, of Cerny's classical mineral-assemblage zones. However, the more complex tantalum-rich pegmatites typically display regular or irregular zoning. Mineral assemblage zonation and distribution of tantalum mineralization are shown in Figures 11–13.

In zoned rare-metal pegmatites, tantalum is normally associated with massive clevelandite or replacement sugary albite in the outer albite zone, as is the case in the Wodgina orebody in the Pilbara (Sweetapple et al., 2001b). Tantalum also occurs in some of the intermediate zones, commonly concentrated in those zones containing muscovite, apatite, and other phosphate minerals, as well as albite, spodumene, zircon, and tourmaline. This is the situation at the Greenbushes deposit in the southwest of Western Australia.

Rare-metal pegmatites that are notable exceptions to this internally zoned morphology are the Mount Cassiterite pegmatite at the Wodgina tantalum mine, and pegmatite bodies located in the Pilgangoora district of the Pilbara region. These aplite–spodumene pegmatites appear to have almost no internal zonation (Sweetapple and Collins, 2002).

During exploration, it is important that the zonation pattern be carefully interpreted to aid in the location of possible tantalum-rich zones. If the pegmatite's depth of emplacement is not more than about 3 m, a series of costeans may be cut at right angles through the pegmatite to provide a better idea of the pegmatite's structure and zonation and to provide access for bulk sampling for chemical analysis.

Mineralization, ore grade, and tantalum resource

It is the albite and intermediate zones that contain tantalite and related tantalum minerals where the ratio of tantalum substantially exceeds that of niobium in the same mineral series. Other tantalum ore minerals found in these zones include wodginite, ixiolite, microlite, and stibiotantalite (Cerny, 1989a, 1993a).

Currently in Western Australia, the minimum resource size for economic recovery from a primary tantalum deposit, or from a number of smaller deposits usually clustered around a centrally located primary processing

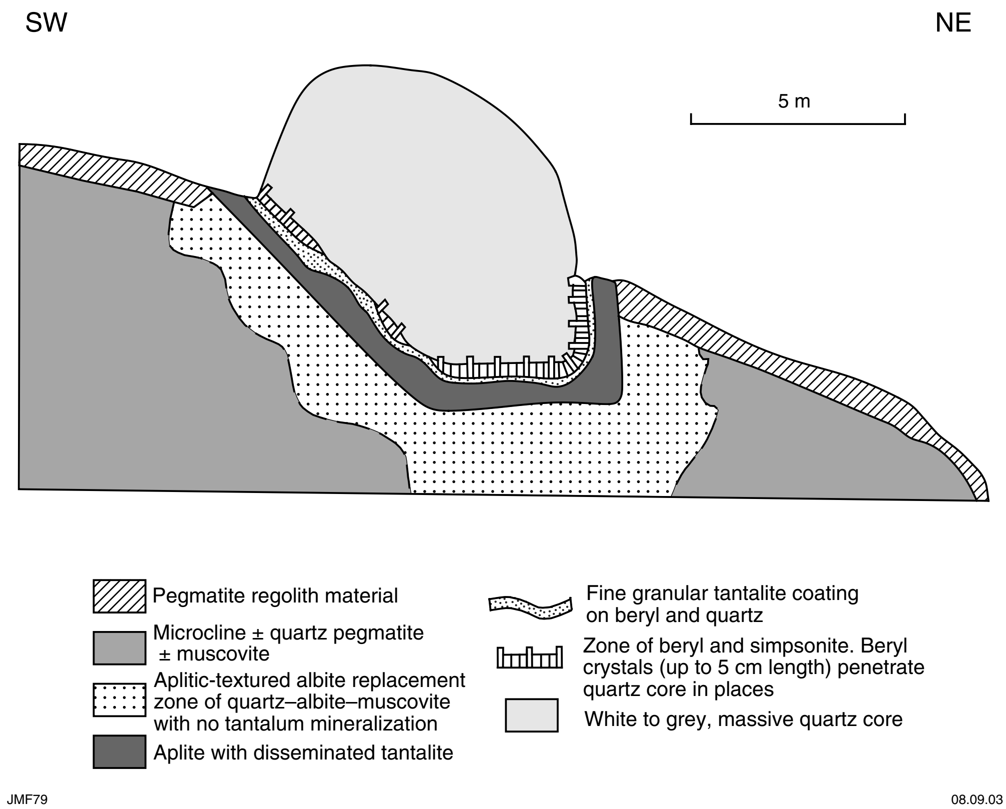

Figure 11. Zonal distribution of mineral assemblages and tantalum minerals around a quartz core at the main Tabba Tabba pegmatite dyke (adapted from Ellis, 1950; and Sweetapple and Collins, 2002)

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Figure 12. Massive quartz core of the main Tabba Tabba pegmatite dyke (looking south). White quartz mass rises to about 2.5 m above the natural land surface

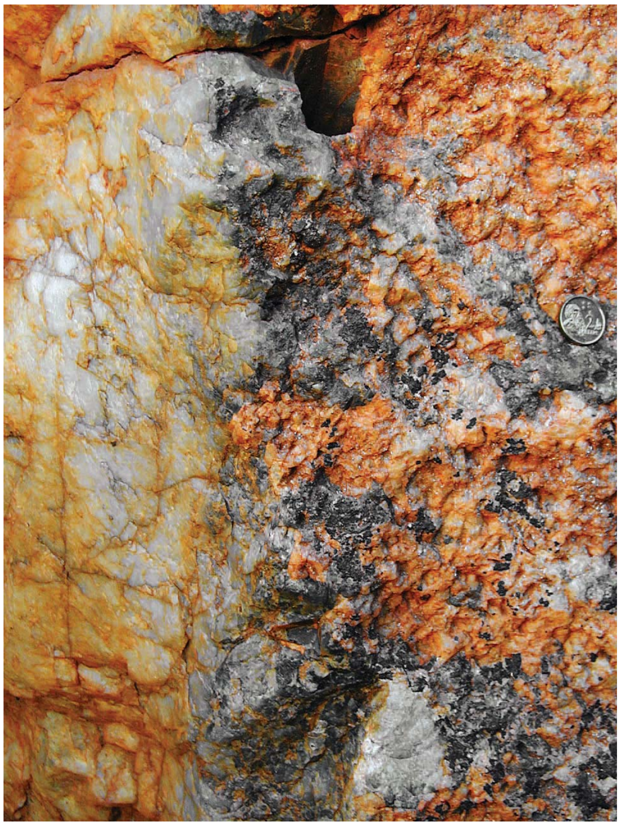

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Figure 13. Detail of the Tabba Tabba pegmatite quartz core. Shows surficial tantalite (dark grey) and hexagonal hole formerly occupied by a large beryl crystal penetrating the quartz core

plant, appears to be about 1.5 Mt. Resources for the large tantalum deposits at Greenbushes and Wodgina exceed this amount by up to two orders of magnitude. At the same time, economic grades for Ta_2O_5 range from 0.018 to 0.055%, with smaller deposits typically requiring grades towards the higher end of the range. Prospects with Ta_2O_5 grades less than 0.010% are considered to be uneconomic at this time.

Alluvial and marine placer deposits

Since virtually all known tantalite alluvial placer deposits in the State have been worked out, the only remaining possibilities are the location of hitherto undiscovered deep-lead tantalum palaeochannel placer deposits, either adjacent to existing hard-rock tantalum mining operations or as palaeochannel drainages from as yet undiscovered primary tantalum deposits in rare-metal pegmatites.

There has been some potential recognized for marine tin–tantalum placer deposits in nearshore deltaic and palaeospit environments located in mouths and lower reaches of rivers along the Pilbara coastline (Hussey, 1980). Low concentrations of tin and tantalum have also been found in gravel- and clay-placer estuarine deposits in Breaker Inlet at the mouth of the De Grey River (Marshall, 1982a). However, no mineral occurrences with tin–tantalum values approaching economic concentrations were located.

Reworking of tailings

Currently, there is some potential for economic recovery of tantalum by the reworking of old tin–tantalum tailings dumps by employing more sophisticated extraction techniques with higher recovery rates. This would be possible in a number of areas in the Pilbara, for example the old tin–tantalum alluvial placer deposits in the Wodgina–Pilgangoora, Shaw River, and Moolyella areas, and in the Gascoyne region around the Yinnietharra – Arthur River area. In some areas, the availability of adequate water supplies to operate alluvial concentration plants may be a problem.

Chapter 6

Tantalum mining and processing in Western Australia

Major hard-rock mining and processing

Western Australia has the world's two largest tantalum mines. These are the Greenbushes mine in the southwest of the State, and the Wodgina mine in the Pilbara region in the northwest. Between them, these two deposits contain at least 75% of known global tantalum reserves (Cutifani, 2001) and supplied about 45% of world demand for tantalum concentrate in 2001.

Greenbushes

Sons of Gwalia's Greenbushes mine is situated about 300 km south of Perth and 80 km southeast of the port of Bunbury. In 2002, the mine had a total reserves and resources estimate of 223.7 Mt at 0.022% Ta_2O_5. These resources comprised proven and probable reserves of 88.6 Mt at 0.022% Ta_2O_5 (estimated to yield almost 20 000 t Ta_2O_5), and measured, indicated, and inferred resources of 135.1 Mt at 0.022% Ta_2O_5 (estimated to yield over 29 000 t Ta_2O_5; Sons of Gwalia Ltd, 2002a). The deposit also contains substantial resources of tin that are recovered during the mining and processing operations.

At Greenbushes, all tantalum–tin ore is recovered from the Cornwall pit (Fig. 14a). Over a period of about 12 years of hard-rock mining in the pit, mining operations have followed the tantalite-rich, moderately to steeply dipping (30–75°) pegmatites downdip, and today the pit is well over 200 m in depth (total design depth is 270 m).

In recent years, the company has taken the decision to extend the mine underground beneath the current pit to maximize recovery of tantalum resources. To this end, a decline was commenced in 2002 in the southeastern corner of the pit to access the orebody at depth (Figs 14b and c). In late 2002, it was decided to suspend work on the decline project pending a resurgence in the global tantalum market.

Mining in the Cornwall openpit is carried out using the drill and blast method on a series of 7.5 m-high benches. These benches are drilled on a 3.5 × 4.0 m pattern and blasted using an emulsion-type explosive. Hydraulic excavators remove the broken rock and load it onto 150 t dump trucks at the rate of 48 000 tonnes/day (Fig. 14d). The material is trucked out of the pit either to tantalum ore stockpiles, or to waste dumps as part of the mine rehabilitation plan. Each week about 30 000 t of tantalum ore is added to the run-of-mine stockpiles being classified by grade and mineral characteristics. This process allows for ongoing selection of optimum ore blends to be fed to the primary processing plant.

Blended ore is first fed to the crushing plant where the material is crushed in a four-stage crushing and screening process. The less than 12 mm crushed ore is conveyed to the newly expanded primary concentration plant with a capacity of up to 1000 tpa Ta_2O_5 concentrate. In the plant, the fine ore is first ground in ball mills to roughly sand-sized particles (<1 mm) before passing through three stages of screening. Coarse gravity separation follows through a series of jigs and spirals, with the coarser material being sent back to ball mills and cyclones for regrinding. Fine gravity separation in spirals and kelsey jigs then removes the tailings, and the tantalum–tin concentrate is sent for upgrading over wet shaking tables and with further kelsey jigging. The primary concentrate is dewatered in cyclones and over a filter bed before passing to the fluidized-bed drier. At this stage, the primary concentrate contains 4–6% Ta_2O_5 and 10–15% Sn. A schematic flow chart of the process is shown in Figure 15, and some of the processing stages are illustrated in Figures 16a–f.

Primary tantalum–tin concentrate is trucked to the secondary concentration plant. The material is first screened into individual size fractions to enhance recovery in the gravity and magnetic separation stages. The first of these stages is dry gravity separation over a dry shaking table (Fig. 17a). This process is followed by high-intensity magnetic separation involving induced-roll and rapid-magnetic separators that effectively separate the magnetic fraction comprising the high-grade Ta_2O_5 concentrate from the non-magnetic tantalum–tin fraction. The magnetic fraction then passes through a roasting stage to remove minor quantities of antimony and sulfides, before emerging as premium-grade tantalite concentrate containing 20–30 % Ta_2O_5 (Fig. 17b).

Processing of the non-magnetic fraction requires a different approach. After flotation and roasting to remove sulfides, the non-magnetic concentrate is smelted in an electric arc furnace to separate the remaining tantalum from the tin fraction. These fractions are tapped off separately, with the tin metal being re-refined in a secondary smelting process. The resulting molten tin is cast into moulds forming ingots (98% pure). The non-magnetic tantalum fraction is also put through a secondary

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Figure 14. Mining operations at Greenbushes: a) the giant Cornwall tantalum–tin openpit that is over 200 m deep; b) construction of the Cornwall pit decline; c) examining diamond drillcore at the Cornwall pit decline; d) mining operations in the Cornwall openpit (photos (a)–(c) courtesy Sons of Gwalia Ltd)

electric arc smelter and the resulting product is granulated to form tantalum glass with an average purity of 15–25% Ta_2O_5. A schematic flow chart of the secondary concentration process is shown in Figure 18.

In the fiscal year 2001–02, the Greenbushes operation produced a record output of 529 t of export-grade Ta_2O_5 concentrate (an increase of 24% on the previous year) and 928 t of tin (Australia's Paydirt, 2002a).

Wodgina

At Wodgina, located about 100 km south of Port Hedland in the Pilbara region, mining for tantalum and tin has been in operation for almost 100 years. Up to 1984, the Wodgina main-lode pegmatite produced 269 t of tantalum and an inferred production of 44 t of niobium. The deposit also yielded 85 t of beryl to the end of 1945. Large-scale mining of the Wodgina main-lode pegmatite began in 1988, based on proven reserves averaging 0.402 Mt at 0.128% Ta_2O_5 and 0.021% Nb_2O_5 (Sweetapple et al., 2001b). Mining continued until 1994 when the deposit was worked out.

Today Wodgina, owned and operated by Sons of Gwalia, maintains its position as the world's second-largest tantalum resource and mining operation. Since 1988, mining activities have shifted to the Mount Cassiterite tantalum–tin pegmatite deposit and, more recently, to the adjacent Mount Tinstone deposit. Both sites are being mined concurrently. Prior to 1988, the Mount Cassiterite deposit produced 308 t of tantalum as well as inferred production of 193 t of tin and 39 t of

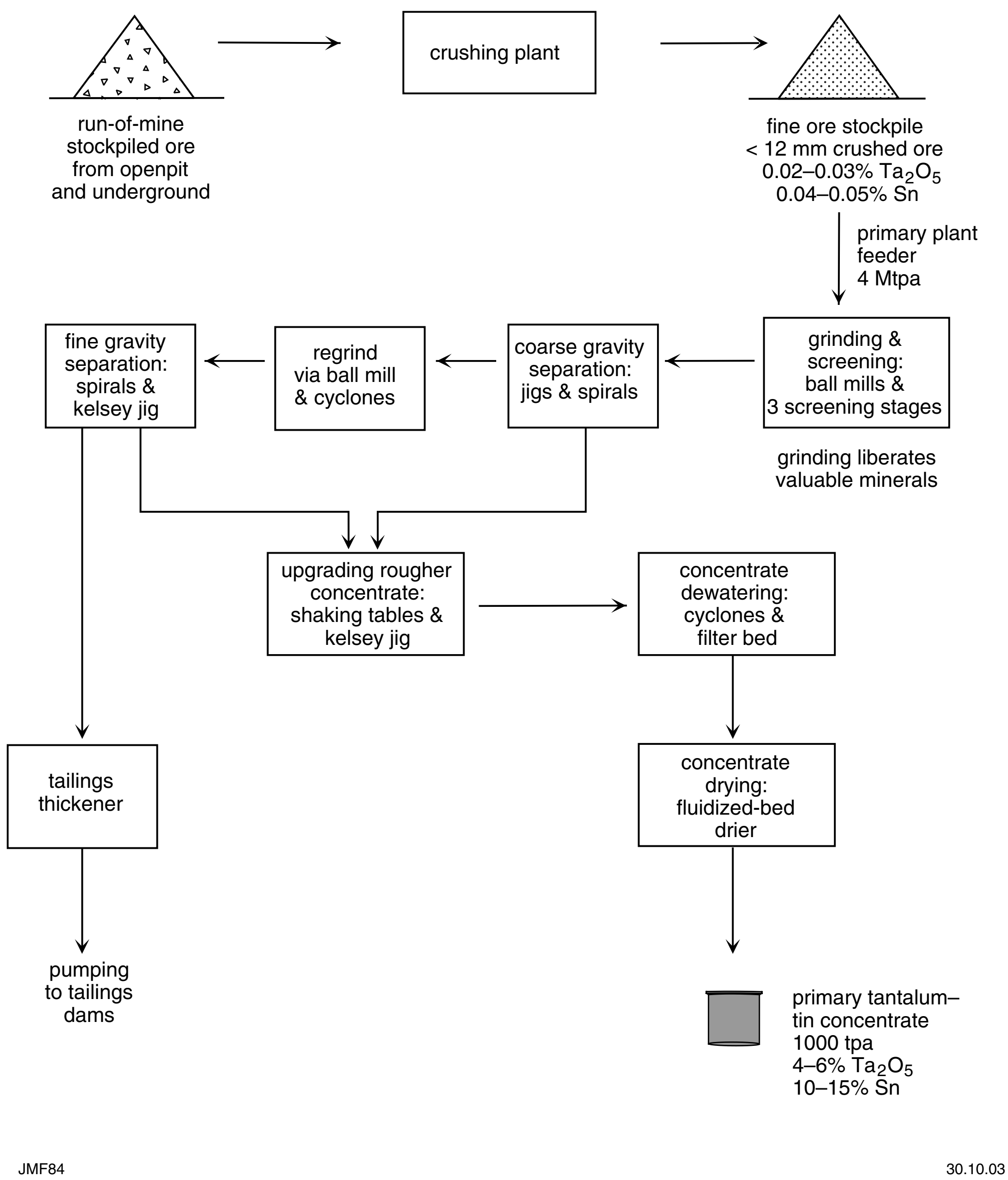

Figure 15. Schematic flow chart of the primary processing of the Greenbushes tantalum–tin concentrate (courtesy of Sons of Gwalia Ltd)

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Figure 16. Primary processing of the Greenbushes tantalum–tin concentrate: a) primary ore crusher; b) ball milling minus 12 mm crushed ore to sand-sized particles (0.5 – 1.0 mm); c) checking the classification screens; d) banks of Derrick screens separating coarse, unliberated tantalum ore particles for regrinding; e) banks of spiral concentrators effecting fine gravity separation of the tantalum ore; f) wet shaking tables for primary ore upgrading to 4–6% Ta_2O_5 concentrate (photos (a), (c), and (e) courtesy Sons of Gwalia Ltd)

Figure 17. Secondary processing of the Greenbushes tantalum–tin concentrate: a) dry gravity separation on an air shaking table; b) final high-grade tantalum concentrate at 30% Ta_2O_5 (photo (b) courtesy Sons of Gwalia Ltd)

niobium. Wodgina first achieved its status as the world's second-largest tantalum source during the 1997–98 fiscal year, when production from Mount Cassiterite reached 77 t of Ta_2O_5, constituting 7.25% of world production.

Current total reserves and resources at Wodgina are estimated at 86.5 Mt averaging 0.027% Ta_2O_5, comprising proven and probable reserves of 63.5 Mt at 0.037% Ta_2O_5 estimated to yield over 23 200 t Ta_2O_5, and measured and indicated resources of 23.0 Mt at 0.018% Ta_2O_5 estimated to yield over 3600 t Ta_2O_5 (Sons of Gwalia Ltd, 2002a).

Currently, mining operations are carried out at elevated locations on both Mount Cassiterite and Mount Tinstone, where large, comparatively flat, open areas have been developed for ease of mining over the low-dipping (15–25°) stacked-sheet pegmatite orebodies (Fig. 19). In these areas the host greenstones, comprising psammites and metabasalt, are weathered up to 80 m below surface and the rare-metal pegmatites, ranging in thickness from 2 to 100 m, are variably kaolinized to at least 50 m depth.

Mining is by conventional drill and blast method, where 5 m benches are drilled and blasted using ANFO (an explosive consisting of ammonium nitrate and fuel oil) or emulsion-type explosives according to prevailing ground conditions. The highly kaolinized nature of many of the pegmatite orebodies tends to make mining and ore crushing a comparatively easy process. In the openpits, ore and waste rock are loaded into large-capacity rear dump trucks using Komatsu hydraulic excavators (Fig. 20). Ore grade control is not necessary as all pegmatite ore grades are currently above marginal cut-off grade, and the contrast between the white pegmatite ore and grey-brown host rocks is usually sharply defined, a factor that assists in substantially reducing ore contamination. Ore is then trucked directly to the run-of-mine stockpile prior to crushing.

In the crushing process, ore is fed from the run-of-mine stockpile into a three-stage crushing plant capable of processing up to 180 tonnes/hour. This process reduces the material to a less than 12 mm ore feed that is conveyed to the recently upgraded primary processing plant with a capacity of 2.5 Mtpa (Fig. 21). After ball milling in which the ore is reduced to roughly sand-sized particles, the ore is passed through a sequence of gravity separation stages involving screening, oversize regrinding, and spiral concentration and scavenging circuits. Falcon concentrators and shaking tables are then used to produce the primary concentrate of about 17% Ta_2O_5. The concentrate, produced as a filter cake containing about 8% moisture, is drummed and trucked to Perth for secondary processing where a concentrate of greater than 40% Ta_2O_5 is produced for export.

In the 2001–02 fiscal year, the Wodgina operation produced 442 t of export-grade Ta_2O_5 concentrate, representing an increase of 41% on the previous year (Australia's Paydirt, 2002a).

Medium-scale hard-rock mining and processing

Currently, there are two companies in Western Australia carrying out medium-scale tantalum mining and processing operations. The first of these, Haddington Resources, operates an openpit mine and concentrating plant at Bald

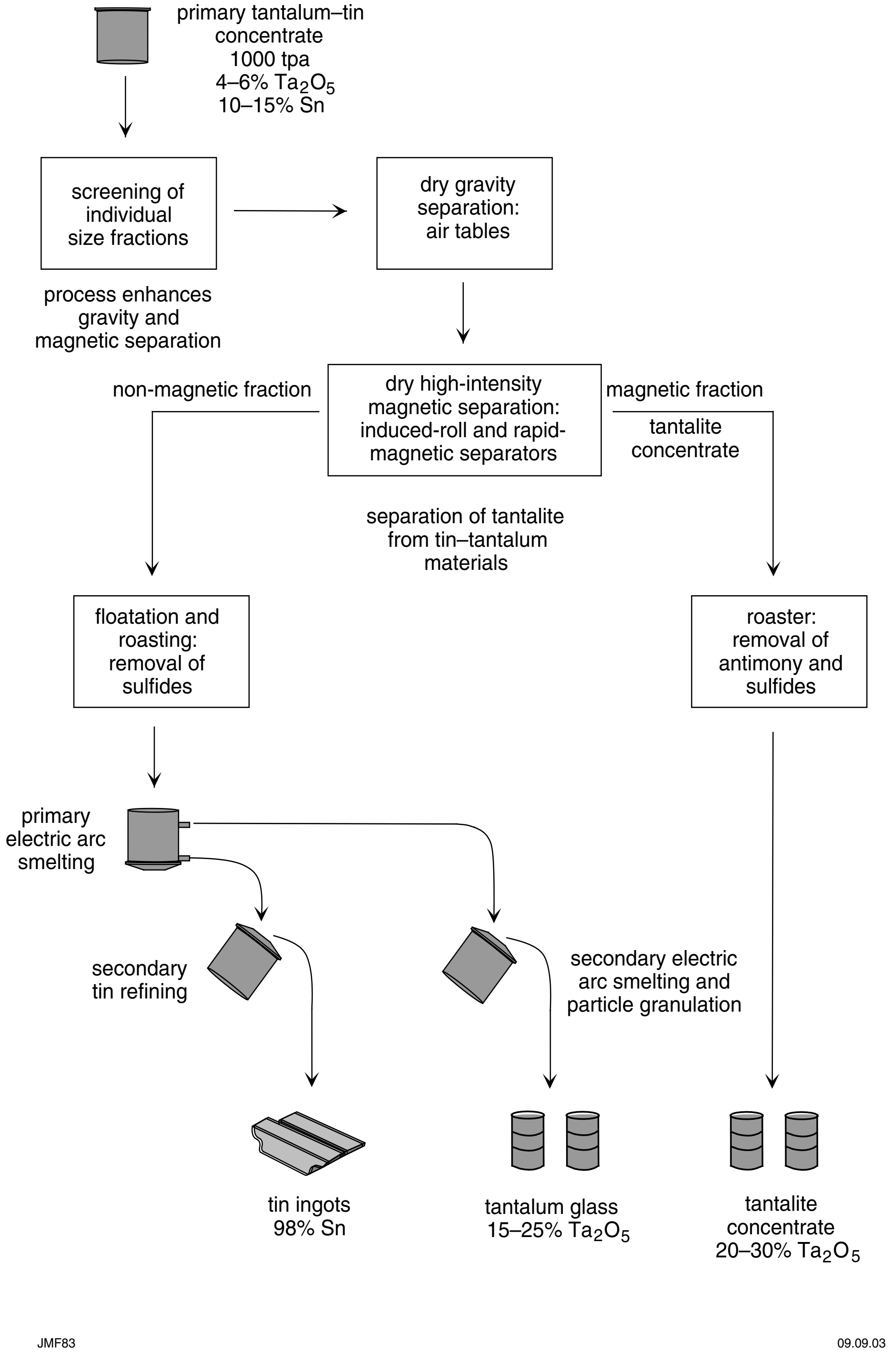

Figure 18. Schematic flow chart of the secondary processing of Greenbushes tantalum concentrate and tin ingots (courtesy of Sons of Gwalia Ltd)

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Figure 19. Drill and blast, and ore-loading operations at the Mount Tinstone openpit, Wodgina mine (looking south)

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Figure 20. Loading kaolinized tantalum-rich pegmatite at the Mount Cassiterite openpit, Wodgina mine

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Figure 21. Ore-processing operations at the Wodgina mine. Conveyor feeds minus 12 mm tantalum ore to the upgraded primary-concentration plant

Hill, about 60 km southeast of Kambalda in the Eastern Goldfields Granite–Greenstone Terrane. This is a comparatively new mining operation that commenced production in July 2001.

The second operation, owned by Tantalum Australia, comprises several openpits and a primary processing plant, and is located at Dalgaranga about 80 km northwest of Mount Magnet, in the Murchison region of the State.

Bald Hill

At Bald Hill, three small openpits are situated over a tabular rare-metal pegmatite hosted by Archaean metasedimentary rocks. The orebody ranges from flat-lying to shallowly dipping, and is located in the near-surface environment. These factors tend to limit overburden removal and improve accessibility to the orebody. Maximum design depth of the openpits will probably not exceed 35 m below surface. In its first 15 months of operation, the company mined 197 000 t of ore from the deposit. In April 2002, a drilling program enabled the recalculation of the remaining tantalum resource to 1.58 Mt at 0.041% Ta_2O_5, comprising measured and indicated resources of 0.90 Mt at 0.041% Ta_2O_5, and inferred resources of 0.68 Mt at 0.041% Ta_2O_5 (Haddington International Resources Limited, 2002a). However, after further drilling the company announced in November 2002 that total resources had been increased to 2.0 Mt at 0.038% Ta_2O_5 (Haddington Resources Limited, 2002).

Openpit mining of the hard-rock pegmatite is carried out by a mining contractor using the drill and blast method (Fig. 22). Broken ore is removed by a 65 t hydraulic excavator and the ore is conveyed to the run-of-mine stockpile on 50 t dump trucks. The hard-rock ore is crushed in several stages, firstly through a jaw crusher and then through a cone crusher. The resultant crushed material is screened and the less than 12 mm fraction conveyed to the fine-ore stockpile and from there to the primary processing plant.

The recently upgraded processing plant, using conventional gravity spiral processing, is designed to treat ore at the rate of 200 000 tpa (Fig. 23). In the plant, the less than 12 mm ore feed is passed through a wet vibrating screen to remove the less than 1 mm fraction and the remaining material is cycled through a vertical-shaft impact crusher (VSI crusher) and vibrating screen a number of times, ultimately reducing most particles to sand size (<1 mm). Particles are then passed through a series of scalping spirals where most of the tailings are removed. Lighter tantalite-bearing material is sent to the ball mill for regrinding and spiralling to liberate the remaining tantalite and eliminate most remaining tailings. Concentrate particles are finally passed through a series of cleaner spirals and are collected, dried, and packed in drums for transport. In the first two quarters of 2002, the plant produced approximately 417 t of primary tantalite concentrate at average grades of around 7.2% Ta_2O_5 (Haddington International Resources Limited, 2002a,b). Recovery rates were in excess of 65%.

Under a six-year licence agreement with Sons of Gwalia, all of the Bald Hill primary concentrate is trucked to the Greenbushes plant for further processing.

Dalgaranga

The Dalgaranga mining and processing operation is centred around the Dalgaranga rare-metal pegmatite deposit that has been worked for beryl and tantalite for about 60 years (Fig. 24). A 150 m-long openpit (30 m wide and 10 m deep) is orientated along the northeasterly strike of the shallowly dipping pegmatite hosted by Archaean greenstones that form part of the southwest extension of the Big Bell regional shear structure. Early in 2002, the Dalgaranga pit was thought to be almost exhausted; however, recent exploration has indicated the possibility of a downdip extension of the pegmatite up to 5–6 m thick and 250 m in length. One drillhole yielded a pegmatite intercept of 6 m at 0.028% Ta_2O_5 and investigations are continuing (Tantalum Australia NL, 2002a).

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Figure 22. Blast hole drilling at the Bald Hill openpit (looking west)

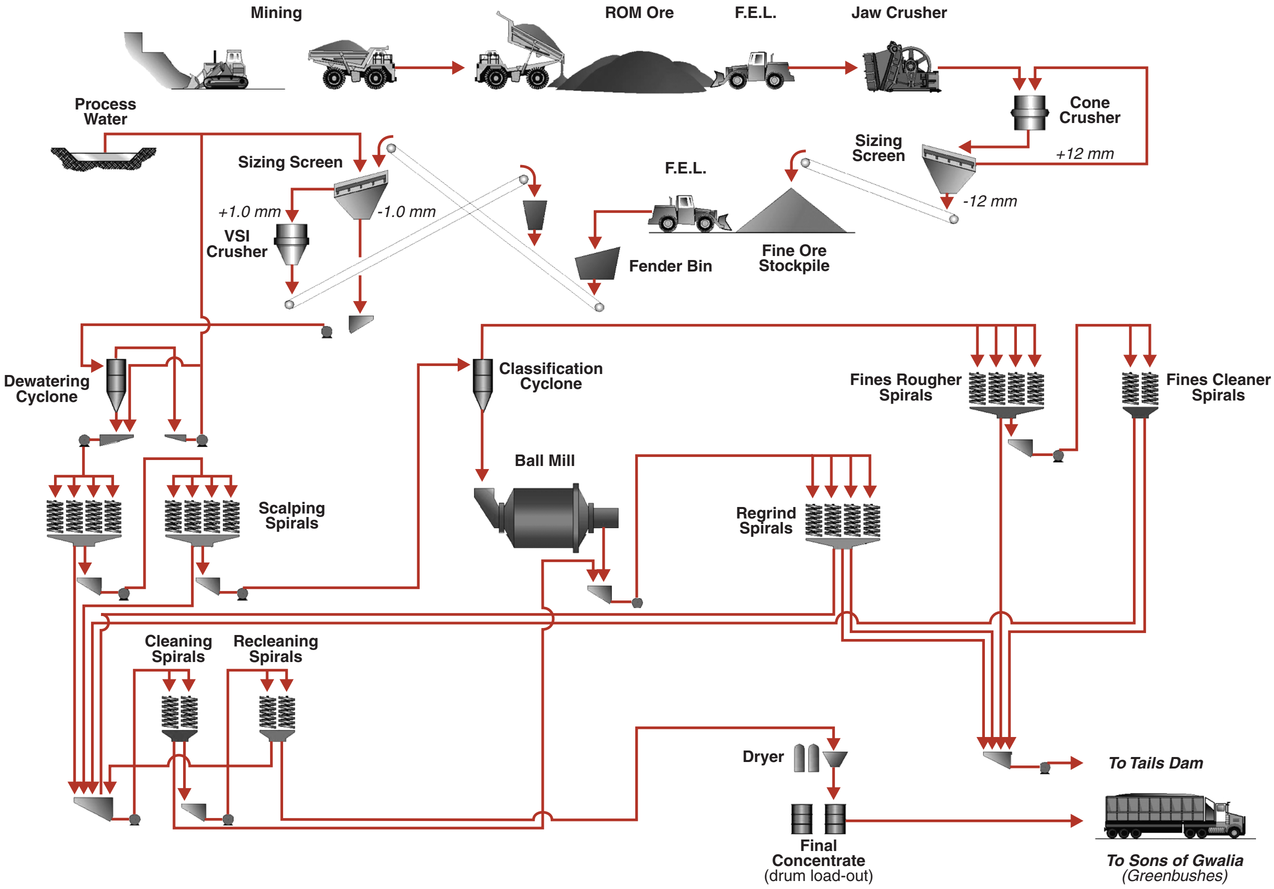

Figure 23. Flow chart of primary-concentrate processing at the Bald Hill operations (after Haddington International Resources Limited, 2001)

Figure 24. The Dalgaranga mine site, looking east

Figure 25. The Dalgaranga primary processing plant

Figure 27. Pebble-sized tantalite (dark) and microlite (light) concentrate that has been trapped by the trommel screen at the Dalgaranga plant

Tantalum Australia currently has access to other local pegmatites, including the nearby the Niobe openpit (formerly known as Mount Farmer), the Breakaway deposit (about 7 km to the east), and the Tantalus prospect (about 27 km to the north-northwest). Other local pegmatites are also under investigation.

In recent years, processing of tantalum-rich pegmatite ore was undertaken by the company on a campaign basis, with most of the material coming from oversize stockpiles. By October 2001, these stockpiles were exhausted and in November–December 130 000 t of ore was mined from the extension to the Dalgaranga openpit. Mining was by drill and blast from hard-rock albitic pegmatite that was hauled to the run-of-mine stockpile at the primary processing plant (Fig. 25).

The 20 tonnes/hour wet primary-concentrate plant was installed on-site early in 2001, initially to treat material from the Dalgaranga and Airstrip pegmatites. The plant is fed by less than 12 mm run-of-mine crushed ore (at an average head grade of around 0.024% Ta_2O_5) that is initially passed through a trommel sizing screen (Fig. 26) in which the 9–12 mm coarse fraction is retained for the extraction of a substantial quantity of pebble-sized tantalite and microlite particles (Fig. 27), whereas the less than 9 mm bulk of the material passes through for further screening. From here, the initial less than 1 mm screened fine fraction is fed through rougher, scavenger, and cleaner spirals, then across wet shaker tables to remove undesirable heavy minerals such as garnet and ilmenite (Fig. 28), and emerges as a fine-grained concentrate containing 8–20% Ta_2O_5.

Figure 26. Trommel screening the ore feed to the Dalgaranga plant; the minus 9 mm feed is sent to the ball mill for grinding, oversized ore is retained for retreatment, and fines are removed to the tailings dam

Figure 28. Tantalite and microlite streams on a wet shaking table at the Dalgaranga plant

The 1–9 mm fraction is passed over a screen, with oversize material being sent to the ball mill for grinding and recycling through the circuits. Ultimately, this circuit produces a final coarse jig concentrate of tantalite and microlite that may range from 25 to 80% Ta_2O_5 (Fig. 29). Plant recovery of Ta_2O_5 is currently running at around 66%.

Drummed tantalum concentrate from Dalgaranga is trucked to the company's secondary-concentrate plant located at Balcatta in Perth. In this operation, the primary concentrate is passed through a series of dry shaking tables followed by high-intensity magnetic separation. In this process magnets spaced along the conveyor belt are adjusted to separate out various grades of Ta_2O_5. Export-grade concentrate is generally in the order of 30–35% Ta_2O_5, but may be upgraded to suit specialized customer requirements.

The Balcatta plant, with a capacity of 230 tpa, currently produces about 45 tpa of Ta_2O_5 for export to markets in Thailand and Japan. The company is currently negotiating to supply markets in the United States, Europe, the Russian Federation, and China, and is gearing up to increase production to between 140 and 180 tpa. This production will initially be sourced from the Dalgaranga area, and later from newer prospective areas in the Gascoyne and Norseman regions of Western Australia and possibly from interstate. In October 2002, the company announced it had secured a three-year sales contract worth $600 000 to supply tantalite concentrate to a new Japanese customer (MiningNews.net, 2002).

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Figure 29. Coarse jig concentrate of tantalite and microlite (25–80% Ta_2O_5) at the Dalgaranga plant

Alluvial mining

For almost 100 years, from the discovery of tin–tantalum deposits in Western Australia in 1888 until about 1980, the bulk of tantalum concentrate was produced by companies and prospectors mining eluvial and alluvial placer deposits. During this time numerous deposits of this type have been utilized, especially in the Pilbara region around Wodgina, Pilgangoora, Moolyella, Tabba Tabba – Strelley, and the Shaw River areas. Other important areas have included Greenbushes in the southwest, and the central Murchison and Gascoyne regions. Today, most known placer deposits have been largely worked out. In the future, it is possible that eluvial or deep-lead placer deposits may be discovered adjacent to newly identified rare-metal pegmatites. The possibility also exists for reworking many old tin–tantalum tailings dumps using superior recovery techniques in a time of significant increase in world tantalum prices.

Wodgina

Several kilometres downstream in the drainage catchment leading from the Wodgina hard-rock tantalum mine are alluvial workings that have been operated by Reynard Australia. It is understood that this deposit was worked until early 2002, when the portable alluvial concentration plant was mothballed due in part to lack of water for concentrate processing. It has been reported that when in operation, feed material for the plant was apparently obtained from around the site and from a number of other local alluvial and eluvial sources around Wodgina (Fig. 30).

This comparatively simple processing plant comprises an initial trommel sizing screen to remove oversize material greater than about 10 mm, and a number of vibrating screens. Heavy tin–tantalum concentrate material is trapped in sluice boxes at the end of the process (Fig. 31).

Pilgangoora

Pilgangoora is located about 25 km northeast of the Wodgina mine and has a number of tin–tantalite alluvial placer deposits that have been worked in streams draining the western side of McPhee Range. In these hills are large, relatively unmineralized pegmatites (up to 300 m in length

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Figure 30. Tantalum-rich gravel-mining operation in a drainage system at the Wodgina Alluvials mine

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Figure 31. Wodgina alluvial tin–tantalum concentrate (11.1% Sn, 5.8% Ta)

and 300 m wide) intruding Archaean greenstone amphibolites and schists. The pegmatites contain tantalum mineralization in a few places.

According to Hickman (1983), most of the recorded tantalum production from Pilgangoora was obtained from alluvial and colluvial placer deposits. However, ore grades were quite variable as mineralogy ranged from good-grade manganotantalite to manganocolumbite and ferro-columbite. Miles et al. (1945) analysed samples from these deposits that varied from 24 to 53% Ta_2O_5 and from 30 to 56% Nb_2O_5. Concentrate production at Pilgangoora up to 1977 is recorded at 33.31 t of tantalite and 13.1 t of tantalite–columbite.

A disused tin–tantalum gravity separation plant is still in evidence at Pilgangoora and is situated adjacent to a large tailings dump (Fig. 32). This plant is relatively sophisticated and has several trommel screens, vibrating jigs, and a series of spiral separators and shaking tables.

In October 2001, Kanowna Lights formed an agreement to acquire the tailings deposits and the gravity separation plant that was to be refurbished to working condition. The project involved reworking the tailings deposits that Kanowna Lights estimated to contain 400 000 m^3 of treatable sands estimated to contain 19 t of Ta_2O_5 (Kanowna Lights Limited, 2001b). The agreement to purchase the project lapsed in March 2002.

Arthur River

In 2001, Kanowna Lights carried out tantalum exploration at Arthur River, about 210 km east-northeast of Carnarvon. Exploration was concentrated along creeks and eluvial slopes that yielded an indicated reserve of approximately 60 500 t of placer-grade material at an average grade of 0.030% Ta_2O_5.

In October 2001, Kanowna Lights completed a 100 000 tpa concentrate plant and associated facilities at Arthur River. The plant operated for only one month before being placed in care-and-maintenance while the company continued negotiations with interested parties to secure a long-term off-take agreement. This situation continued until the third quarter of 2002, when the company announced it had sold its 70% interest in the project to Rare Resources who were the holders of the remaining 30%. Negotiations on future ownership of this project are continuing.

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Figure 32. Disused alluvial tin–tantalum processing plant at the Pilgangoora Alluvials deposit

Chapter 7

Manufacturers, processing, and primary products

Tantalum manufacturers

There are eight principal manufacturers of tantalum raw materials around the world. These are H. C. Starck in Germany (also with operations in the USA, Thailand, and Japan); Cabot Performance Materials in the USA; Ningxia Non-ferrous Metals Smelter in China; Metallurg International Resources in Brazil; Showa Cabot Supermetals, and Mitsui Mining and Smelting in Japan; NAC Kazatomprom in Kazakstan (Ulba Metallurgical Plant) in the Russian Federation; and AS Silmet in Estonia. These companies process a variety of tantalum powders, ingots, primary metal products, alloys, and chemicals.

A number of manufacturers also specialize in the recovery of tantalum from tin slags. This form of recovery occurs in Thailand (Thailand Smelting and Refining Company Ltd (Thaisarco) from tin ores sourced in Thailand, Malaysia, and Indonesia), and in Nigeria (Nigerian Mining Corporation from tin ores from the local Jos Plateau). In China, there are a number of companies processing ores and tin slags for tantalum recovery and chemical manufacture. In Western Australia, Sons of Gwalia manufacture an export-grade tantalum glass recovered from tin slag at its Greenbushes operation.

In addition to some of the companies listed above, there are numerous companies around the world specializing in the downstream processing of tantalum raw materials. These operations produce a vast array of value-added tantalum products in many diverse industries. Industrial applications for tantalum are discussed in detail in Chapter 8.

Processing of tantalum metal

Since their chemistry is very similar in terms of ionic radius, valence, and electronegativity, tantalum and niobium are quite difficult to separate. This is achieved by chemical processes instead of the usual smelting techniques used in the recovery of most metals. To initiate this process, the $Ta_2O_5 - Nb_2O_5$ concentrate is attacked by a strong hydrofluoric–sulfuric acid mixture to bring the tantalum–niobium ions into solution. The liquid is then subjected to a solvent extraction process using methyl iso-butyl ketone. This liquid–liquid separation technique absorbs the tantalum and niobium into the organic ketone phase, leaving the impurities in the inorganic aqueous phase. These phases form distinct layers that can be easily separated. The niobium is then removed from the ketone using dilute acid, followed by the tantalum that is reacted with acid ammonium fluoride to form potassium fluorotantalate. In further processing, the potassium fluorotantalate is either reduced by reaction with sodium (Fig. 33), or electrolyzed in the molten state, to form tantalum metal powder.

During the reduction process, control parameters are invoked to produce two different grades of tantalum powder. The first of these is capacitor-grade powder typically displaying a very high surface area, and the second is high-density metallurgical-grade powder. The high surface-area powder is pressed into porous pellets that are then sintered for use in tantalum capacitors.

Metallurgical-grade powder is melted by an electron-beam furnace (EB) and/or a vacuum arc remelting process (VAR) to yield tantalum ingots. These processes are carried out in a vacuum or inert gas atmosphere because of tantalum's affinity for oxygen, nitrogen, and carbon at elevated temperatures. Tantalum ingots are normally melted three times to volatilize interstitial gases and most metallic impurities. Refractory metal impurities such as niobium, molybdenum, and tungsten are difficult to

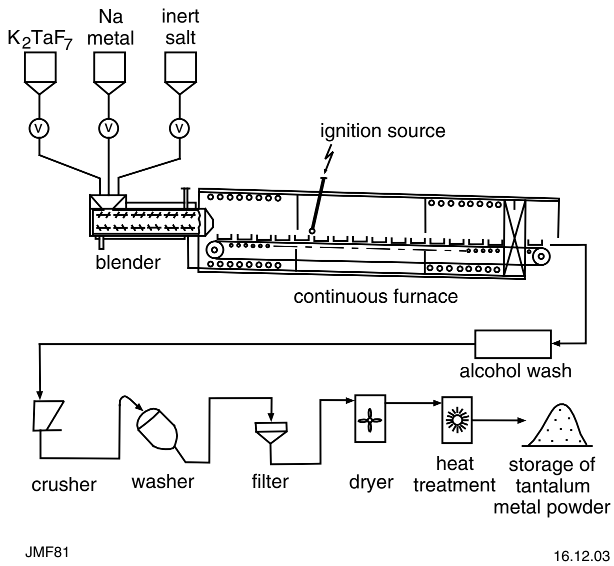

Figure 33. Production of tantalum metal powder. Potassium fluorotantalate (K_2TaF_7) is reduced by sodium metal in a continuous furnace process (modified from Albrecht, 1989)

remove and may require additional processing. The EB process has been shown to be more efficient; however, VAR is a lower cost process and is capable of producing finer grain-size metal than is the case with EB. Finer grain-size metal is a useful characteristic that reduces the amount of work required for the production of annealed tantalum products. The VAR process is generally used in the casting of small tantalum ingots, whereas tantalum producers such as Cabot Performance Materials use 1200 kW EB furnaces to produce 2000 kg tantalum ingots with a 99.999% purity after three castings.

In Western Australia in mid-2002, exploration and mining company Tantalum Australia (formerly Australasian Gold Mines) acquired the rights to carry out research and development on tantalum metal production in conjunction with Boston University, USA. The research program involved the development of a revolutionary new process to produce tantalum metal within three to five years. The process, known as solid oxygen-ion-conducting membranes (SOM), has already been demonstrated to produce magnesium metal from magnesium oxide in a laboratory environment and a licence has been granted to commercialize the process. The current research program aims to adapt the process to directly convert tantalum oxide (Ta_2O_5) concentrate into high-purity – low-oxygen tantalum metal.

In the SOM process, a stabilized zirconia electrolyte would separate the anode from the melt containing the Ta_2O_5 to be reduced. An electric current would then be applied to the cathode placed in the melt. When the electric potential between the anode and cathode exceeded the dissociation potential of the Ta_2O_5, tantalum cations would be reduced to tantalum metal at the cathode and oxygen released at the anode. The potential between the electrodes may only be increased to the level where the potential at the melt–zirconia interface does not exceed the dissociation of the solid zirconia in order to prevent undesirable oxides also being reduced at the cathode. Experiments to date have shown that metals can be produced by this process from suitable ionic melts at temperatures of 1200–1500°C and current densities of greater than 1Å/cm^2. This process also eliminates the production of halogen gases produced in conventional tantalum reduction processes (Mining Journal, 2002a).

Tantalum Australia predicts that this process could result in a tantalum yield of about 95% instead of a yield of around 70% obtained using current technology, and could result in a capital and operating cost reduction of at least 30%. The company intends to undertake the research program in stages and, if successful, intends to scale up to a laboratory pilot plant before proceeding to the construction of a major processing plant in Western Australia. This would be the first vertically integrated tantalum-production business in Australia, starting with the mining of tantalite ore and ultimately producing high-grade tantalum metal.

In October 2002, it was reported that the Boston University research team had successfully employed the SOM process to produce almost pure tantalum metal from tantalum oxide in laboratory trials. The research program is continuing (MiningNews.net, 2003a).

Metallurgical processing and fabrication

For most applications, tantalum is a comparatively easy metal to work using techniques common to many other metals. It is superior to most refractory metals in terms of its ductility, workability, and welding properties. It can be processed at room temperature and works like steel in drawing, stamping and spinning processes, and will not spring back when stamped, forged, or annealed.

Consequently, experienced personnel are able to carry out bending, roll forming, and welding with relative ease. In forming operations tantalum behaves in a manner similar to copper. While operations such as forming, bending, stamping, blanking, and deep drawing are normally carried out at room temperature, forging of heavy sections may be carried out by heating the metal to 315–430°C. Due to its workability, tantalum can be cold-formed either parallel or at right angles to the grain of the metal, and its high ductility allows it to undergo cold reductions of greater than 95% without metal fatigue. It can also be machined, welded, brazed, and riveted.

It should be noted that annealed tantalum has a ‘sticky’ property, similar to that of copper, lead, and stainless steel, that requires special treatment during fabrication to prevent the metal seizing, tearing, or galling during stamping, drawing, and machining. Galling is excessive friction between the metal and the cutting tool that results in localized welding and subsequent spalling and roughening of the tantalum metal at the cutting site.

Forming and stamping

Form and stamping processes for tantalum metal may be accomplished using all the usual sheet-forming operations common to that of mild steel. Operations are normally carried out at room temperature using metal with a thickness usually between 0.1 and 1.5 mm

Form stamping

Form stamping is a process, accomplished using the above criteria, in which tantalum metal may be reduced in thickness, and/or cut or bent to precise shapes in a stamp mill. Providing precautions are taken to prevent seizing or tearing of the metal, tantalum sheet within this thickness range can be bent at angles up to 180° without any sign of metal fatigue. In form-stamping operations, dies are usually made of steel, except where there is considerable slippage of the metal, in which case aluminium–bronze or beryllium–copper dies are used to reduce galling. Annealed tantalum assumes a permanent shape during forming as it does not spring back from the dies.

Blanking or punching

Blanking or punching operations are carried out using a punch press in which tantalum metal is cut into flat shapes (blanking) or punched into contoured shapes (punching).

In these processes, the situation is the same as for form stamping in relation to ambient temperature, metal thickness, and use of appropriate dies. Production of quality tantalum blanks in this operation requires the clearance between the punch and the die to be equal to 6% of the thickness of the tantalum metal being worked. A suitable lubricant is required to prevent scoring of the dies.

Deep drawing

Only annealed tantalum sheet should be used in the shaping of tantalum blanks by deep drawing. In a single-draw operation, the depth of the draw is equal to, or greater than, the diameter of the original tantalum blank. Since tantalum does not work-harden as rapidly as most metals, the work-hardening is most apparent at the surface of the drawn part and decreases towards the deepest part of the draw. In multiple-draw operations, the first draw should have a depth of less than 40–50% of the blank's diameter. In this process, the dies are aluminium–bronze and the punch is made of steel, provided that the slippage is minimal. The process must be lubricated with a special oil or wax.

Spinning

Tantalum parts can be formed under the conditions listed above by steel or brass roller wheels spinning at peripheral speeds of about 1.5 m/s. The spinning tool travels lightly in long sweeping stokes over the tantalum part being spun, using wax or soap as a lubricant. The spinning technique avoids the undue thinning of the tantalum during the forming process. Once the spinning process is complete, the edges of the tantalum metal are cut off so that the most highly stressed metal sections are removed.

Annealing

Annealing of tantalum is carried out by heating the metal to temperatures between 1100 and 1370°C in a high vacuum to prevent the metal reacting with hot atmospheric gases. The annealing process tends to toughen the metal and prevent the development of internal stress.

Machining

Turning

Tantalum may be satisfactorily turned on a lathe at slow–medium speeds of 0.1 – 0.4 m/s using type C2 high-speed steel cutting tools, or at medium–high speeds of 0.3–0.5 m/s using cemented-carbide cutting tools. It is essential to maintain the correct speed and ensure cutting tools are kept sharp to prevent tearing of the metal (especially annealed tantalum). Generous use of lubricant is required during the cutting process. Due to its greater surface hardness, annealed tantalum does not machine as well the unannealed metal. Galling may be prevented by careful control of metal feed rates and lathe speeds. If galling occurs it will be visible as tears in the surface of the metal.

Milling and other processes

Milling and other processes such as drilling, threading, tapping, and filing of tantalum are similar to the procedures listed above under turning, and involve lubrication of the cutting site, using high-speed drills, light feed-metal rates, and keeping tools sharp and free of tantalum chips. If these procedures are followed, high-quality tantalum products can be produced.

Other mechanical processes are riveting and grinding. Rivets are made from tantalum wire or rods and are affixed to tantalum metal sheets at room temperature. Grinding of cold-worked tantalum is quite difficult and grinding annealed tantalum is almost impossible. Due to the fact that most grinding wheels load rapidly when grinding tantalum, this process should be avoided if possible. However, it is possible to grind cold-worked tantalum with fair results using specially made aluminium-oxide grinding wheels that tend to have less of a loading problem.

Welding

There are a number of methods available for welding tantalum. These include resistance welding where tantalum may be welded to itself and to a number of other metals, and fusion welding using either tungsten inert-gas or electron-beam methods where tantalum parts are joined with strong ductile welds. Prior to welding, it is essential that the metal to be joined is thoroughly cleaned to ensure no dirt or oxides are present.

Resistance welding

This process is carried out using conventional industrial-grade electric welding equipment. Tantalum sheets, especially thin gauge metal less than 0.8 mm in thickness, are routinely spot welded together with the sheets submerged in water to prevent metal oxidation and to provide efficient cooling. Tantalum tubes formed from sheet are commonly welded along the seam by a continuous spot-welding process. It is important to note that this form of spot welding is not as strong as fusion welds and is only used for applications where applied pressures are low.

Fusion welding

Tungsten inert-gas welding

Tungsten inert-gas welding (TIG), also known as gas–tungsten arc welding, is carried out in an enclosed inert gas atmosphere consisting of argon, helium, or a mixture of the two. At temperatures above 320°C, the inert gases protect the tantalum metal in and around the weld site from absorption of oxygen, nitrogen, or hydrogen that may cause oxidation and subsequent embrittlement of the metal. Rapid cooling of the heat-affected area can be achieved through the use of copper chill bars. Extremely high ductility of the weld can be achieved by first evacuating the welding chamber before the inert gas is introduced.

Electron-beam welding

This form of welding is commonly used to weld thick sections of tantalum metal together. Welds produced by this method are up to 19 mm narrower and deeper than those produced by other welding techniques. This method is also used to reduce distortion in thin tantalum sections by virtue of its narrow weld zone.

Cleaning and grit blasting

To achieve satisfactory results from tantalum machining, welding, and other processes, it is vital that the metal be thoroughly cleaned. This involves chemically cleaning the tantalum parts in a saturated solution of potassium dichromate (or chromium trioxide) in concentrated sulfuric acid at approximately 110°C. The metal is rinsed in hot distilled water to remove all traces of the chromic acid solution. The parts are then dried in warm, dust-free air prior to further processing.

Tantalum metal destined for use as components in electronic vacuum tubes is often subject to grit blasting to increase the available radiation surface. This is accomplished by blasting the metal for a few seconds with fine steel grit. The metal is then treated with a hot, strong hydrochloric acid solution to remove all steel grit particles. The parts are then thoroughly washed in distilled water and then cleaned chemically as outlined above.

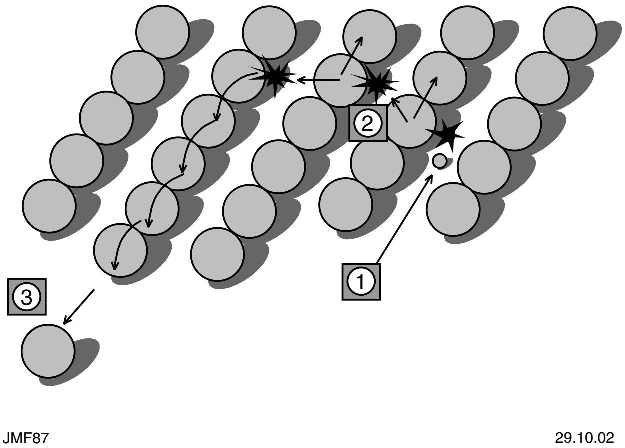

Figure 34. Representation of the cascade effect in sputtering: 1) a plasma ion penetrates the atomic structure of the sputtering target and collides with a lattice atom. Sufficient energy is transferred to the lattice atom, dislodging it from its lattice position; 2) the dislodged target atom distributes its momentum to neighbouring atoms through subsequent collisions. Momentum is transferred most efficiently along the close-packed directions in the crystal lattice; 3) sufficient momentum is eventually transferred to a surface atom, causing it to be ejected from the target along a trajectory parallel to the close-packed direction of the lattice (after Michaluk, 2000a)

Coating techniques

Sputtering

Sputtering, also known as physical vapour deposition (PVD), is a process whereby a source material known as a sputtering target, coated with a particular metal or chemical compound, is bombarded by high-energy plasma ions. The impact of the plasma ions causes a momentum exchange with the atoms in the sputter target, pushing the atoms deeper into the target substrate. It is estimated that an argon (Ar^+) plasma-induced ion at 500 electron volts is capable of penetrating a tantalum target to a depth of 13 angstroms. Further ion impacts cause a cascade effect and atoms at the target surface are ejected in a gaseous state (Fig. 34). Since these particles are not in thermodynamic equilibrium, they return to their solid state upon colliding with any substance in the plasma chamber.

To achieve optimum sputter yield, the high-energy field induced in the plasma chamber is modified by the application of an alternating radio-frequency current, magnetic field, or bias voltage to the sputter target. The process requires very high-quality tantalum metal targets in terms of chemical purity (≥99.99%), fully recrystallized grain size greater than or equal to 100 µm, and a uniform globular particle texture.

This process finds important industrial applications in the deposition of thin tantalum films onto silicon wafers used in semiconductor devices such as microprocessors and memory chips, and also as resistive paths in integrated circuits. Another important process is the application of thin optical coatings of tantalum onto flat glass, lenses, and mirrors. Other examples of tantalum sputter coating include wear-resistant thermal ink-jet print heads, and magnetic recording heads. However, it is predicted that the process's greatest potential lies in the production of tantalum diffusion barriers in the next generation of integrated circuits (Michaluk, 2000a).

It is important to recognize that numerous tantalum chemical compounds are also used in this process to produce compound coatings for a wide variety of applications. Most tantalum compounds (discussed later in this chapter) may be used in this process, apart from liquids such as tantalum ethoxide and oxalate.

Chemical vapour deposition

Chemical vapour deposition (CVD) is a chemical process for depositing thin films of various materials as coatings onto a variety of target objects. In the CVD process, a substrate covered with the desired chemical compound is exposed to one or more volatile vapours that cause a chemical reaction or decomposition of the chemical compound on the substrate, thus forming thin films of the desired material on the target object. Volatile byproducts, often produced by the reaction, are removed by gas flow through the reaction chamber.

There are a number of different forms of the CVD process in common use by industry:

- Metal–organic CVD (MOCVD) — processes based on metal–organic precursors;

- Plasma-enhanced CVD (PECVD) — a process utilizing a plasma to enhance the chemical reaction rate of the precursors. This process promotes relatively low-temperature deposition of films on substrates such as glass and plastic, and is often critical in semiconductor manufacture;
- Rapid thermal CVD (RTCVD) — processes employing heating lamps or other methods to heat only the wafer substrate rather than the gas or chamber walls, in order to reduce undesirable gas phase reactions;
- Atmospheric pressure CVD (APCVD) — CVD reactions at normal atmospheric pressure;
- Low-pressure CVD (LPCVD) — processes carried out below atmospheric pressures to reduce unwanted gas phase reactions and improve film uniformity over the whole surface;
- Ultra-high vacuum CVD (UHVCVD) — processes carried out at very low pressures in an evacuated reaction chamber;
- Atomic layer CVD (ALCVD) — a process involving two complementary volatile precursors required to complete the reaction of the substrate surface by a number of alternate exposures to each precursor.

CVD methods involving tantalum chemical compounds include the MOCVD process in which tantalum ethoxide liquid is reacted to produce thin tantalum pentoxide dilectric coatings. Tantalum pentoxide films are also deposited using plasma-enhanced CVD on silicon semiconductor wafers, for example, nano-optical waveguides. The PECVD process is used to deposit films of tantalum nitride and tantalum carbide as high-temperature corrosion and/or wear-resistance barriers on other metals. The LPCVD process has been used with tantalum oxalate to cover proportionately large areas for optical coatings and computer memory chips.

Table 9. Average impurity values for primary tantalum metal

	Parts per million
O	130
C	73
N	59
H	12
Nb	143
W	54
Mo	35
Si	25
Cr	10
Fe	10
V	10
Ca	10
Al	8
Ni	8
Ti	8
Zr	7
Mg	6
Sn	6
Co	6
Mn	6
Cu	3
Li	2
K	2
Na	2
U	0.004
Th	0.004
Total impurities	**635.0**

SOURCES: Cabot Corporation (2002a); National Electronic Alloys Inc. (2002); Ulba Metallurgical Plant (2002)

Tantalum primary products

Tantalum metals

In all of these primary products it is a requirement that the purity of the tantalum metal is very high, generally in excess of 99.9%, together with very low levels of impurities. Average values for impurities contained in primary metal products are given in Table 9.

Tantalum wire

As previously noted, pure tantalum has a high tensile strength, is extremely malleable and ductile, and is easily worked at room temperature. Under these conditions it can be drawn into a very thin wire. Most wire produced is high-quality capacitor grade and is used as lead wires connecting tantalum capacitors to microcircuit boards. Capacitor-grade wire is specially engineered to enhance straightness, grain-size stability, and ductility. Tantalum wire is also used in metallurgy as a filament for evaporating metals such as aluminium. During production, wire is drawn and spooled in at least seven thicknesses ranging from extremely fine grade with a diameter of 0.03 mm to comparatively thick grades with a maximum diameter of 3.0 mm. Commonly produced wire thicknesses are 0.25, 0.3, 0.4, 0.6, 0.8, and 1.0 mm diameter.

Other tantalum metal products

Apart from tantalum wire, the metal is fabricated into many other primary tantalum metal products, mainly intended for added-value processing by secondary manufacturers producing finished tantalum products for industrial applications. These primary products include tantalum foil, sheet, plate, rod, welded tube, shot, pellets, chips, ribbons, rivets, sputtering target plates, and crucibles. Typical specifications for some of these products are given in Table 10.

Tantalum alloys

Today, tantalum is incorporated in numerous so-called ‘super alloys’ that find applications in aerospace structures, specialized metal fabrication, weapons systems, turbine blades for jet engines, and power station generators. Tantalum is alloyed with many metals, especially the refractory metals niobium, tungsten, molybdenum, and hafnium. Being mutually soluble, the

Table 10. General specifications for tantalum primary metal products

Tantalum primary metal product	*Specifications*
Foil	21 grades with thickness 0.01 – 1.0 mm, width 30–120 mm, spooled in rolls
Sheet	More than 6 grades with thickness 1.27 – 3.6 mm, width 50–610 mm, finer grades spooled in rolls
Plate	More than 5 grades with thickness 6.35 – 25.4 mm, width 50–610 mm
Wire and ribbon	Pure tantalum and tantalum (90.0 – 97.5%) – tungsten (2.5 – 10.0%) alloys. Wire has various diameters of 0.18 – 3.14 mm, wire less than 1.0 mm diameter spooled in rolls. Ribbon has widths of 0.76 – 14.6 mm and thicknesses of 0.025 – 0.25 mm
Rod	Pure tantalum and tantalum (97.5%) – tungsten (2.5%) alloy, numerous diameters of 1.6 – 152 mm. Lengths of 0.5 – 4.0 m for rods of 1.6 – 6.0 mm in diameter and 0.1 – 0.4 m for rods greater than 6 mm diameter
Tubing	More than 6 outside diameters of 25.4 – 89 mm
Shot and pellets	Shot: 3.0 mm diameter Pellets: 3.0 mm diameter × 6.5mm length and 6.5 mm diameter (spherical)
Chips	Thickness 20 mm, length 51 mm, width 51 mm
Sputtering target plates	Require the use of the highest purity triple-melted EB tantalum ingots for manufacture. Disks in various diameters of 25–325 mm, thickness grades of 1.5 – 10 mm
Crucibles	Corrosion-resistant vessels for the chemical industry. Typical dimensions are width of 25–29 cm, height of 13–16 cm, and wall thickness of 1.25 mm

SOURCES: Geolite (2002); Ulba Metallurgical Plant (2002); National Electronic Alloys Inc. (2002); H. C. Starck (2002); Electronic Alloys UK (2002); Scientific Instrument Services Inc. (2002)

refractory metals form solid-solution alloys with each other in any proportion. Most tantalum alloys are used in applications where resistance to high-temperatures and/or chemical corrosion are of prime importance, as well as in other special-use applications. A number of these alloys are listed in Table 11.

Capacitor-grade tantalum powder

Development

Tantalum is generally the preferred material for capacitor manufacturers because it can be purified at high temperatures and can be worked mechanically. In addition, improvements in tantalum powder technology have led to a substantial increase in purity and surface area of the powder, resulting in increased capacitance in smaller spaces. Since 1960, the capacitance voltage per gram (CV/g) of tantalum powder has increased from about 5000 CV/g to about 65 000 CV/g in 2000. In 2002, it was estimated that 65% of total tantalum powder production was destined for the tantalum capacitor market.

Capacitor powder

Over the past 40 years, improvements in capacitor powder technology have not only dramatically reduced the physical size of tantalum capacitors incorporated in today's microcircuits and at the same time increased capacitance values, but have also vastly increased their reliability over a wide range of operating conditions. The three grades of capacitor-grade tantalum powder made by industry are discussed below.

Angular (or EB) powders

In this process, high-purity electron-beam (EB) tantalum ingots are hydrogenated, ground, dehydrogenated, diffused, and grated in an argon medium to produce tantalum powders. These incorporate both angular and flake-shaped particles that have been specially agglomerated to achieve a predetermined surface area and capacitance range. Powders are used in high-voltage applications where high reliability is a requirement.

Nodular powders

These materials are produced by the sodium chemical-reduction method for tantalum. The products have high surface areas ranging from 0.3 to 0.9 m^2/g and have excellent handling and flow characteristics for the production of small capacitor anodes with good weight and capacitance control. They are used in applications requiring high capacitance and low voltage.

Flake powder

This product, manufactured by the Cabot Corporation, is also produced by the sodium reduction method, and has the same properties of high surface area, and handling and flow characteristics as for nodular powders. However, the flake particles are physically formed by a patented process that results in a particle aspect ratio of 20:50 µm. This process extends the capacitor operation to applications with medium capacitance and voltage requirements (Cabot Corporation, 2002b).

Tantalum chemical compounds

A large range of tantalum chemical compounds are manufactured by large tantalum-processing corporations in the United States, Germany, China, and Brazil, together with a number of subsidiaries and other companies operating in countries including Canada, the United Kingdom, Japan, Kazakhstan, Estonia, Thailand, and Taiwan.

Tantalum chemical compounds are manufactured for a diverse range of applications that includes tantalum-metal and aerospace-alloy manufacture, catalysts, electronic components, hard-metal tools, optical coatings, and specialized lubricants. A summary of the main tantalum chemical compounds currently manufactured is given in Table 12.

Table 11. Tantalum alloys

Alloy	*Tantalum (%)*	*Other metals (%)*	*Comments*
Tantalum–rhenium	≥98.5	Rhenium (≤1.5)	For applications with good mechanical properties up to 3000°C
KBI-6/NRC 76[(a)]	97.6	Tungsten (2.4)	For low-temperature strength and high corrosion-resistance applications. Easily fabricated
KBI-10	90.0	Tungsten (10.0)	For use in corrosive environments and high temperatures up to 2480°C. Has twice the tensile strength of pure tantalum. Easily fabricated
Tantalum–manganese	75–90	Manganese (10–25)	Used in anode manufacture
KBI-40	60.0	Niobium (40.0)	Used in the electronics and chemical-processing industries. Relatively easily fabricated. Tendency to gall
$Ta_{50}Ru_{50}$	50.0	Ruthenium (50.0)	Application as high-temperature 'shape-memory' alloys
Tantalum–aluminium	50.0	Aluminium (50.0)	Sputtering of ink-jet printer heads and thin films for Ta–Al film resistors
Tantalum–cobalt	na	Cobalt (na)	Aerospace structures and jet turbines
Iron–tantalum	na	Iron (na)	Aerospace structures and jet turbines
Alloy 718	Tantalum and niobium (5.0)	Nickel (52.5) Chromium (19.0) Iron (18.5) Molybdenum (3.0)	Aerospace components and nuclear applications. High-strength fatigue and stress rupture properties up to 700°C and oxidation resistance up to 980°C
Alloy 625	Tantalum and niobium (3.6)	Nickel (61.0) Chromium (21.0) Molybdenum (9.0) Iron (2.5)	Aerospace structures and jet turbines. Has good corrosion resistance from cryogenic temperatures up to 1100°C
Chromium–tantalum	2.0	Chromium (97.4) Titanium (0.1) Silicon (0.5)	High-temperature jet turbine blades
Tantalum–titanium	80	Titanium (20)	
Tantalum–zirconium	75	Zirconium (25)	
Titanium–tantalum	5	Titanium (95)	
Aluminium–niobium–tantalum	10	Aluminium (70) Niobium (20)	

SOURCES: Cabot Corporation (2002a); H.C. Starck (2002); Espi Metals (2002); Principal Metals (2002); Metal Suppliers Online (2002)

NOTES: There are many other tantalum alloys with limited additional information available. These include cobalt–tantalum–chromium, cobalt–zirconium–tantalum (CZT), iron–tantalum–chromium, and cobalt–tantalum–chromium–platinum

(a) KBI and NRC are trademarks of the Cabot Corporation and H. C. Starck respectively
na not available

Table 12. Tantalum chemical compounds

Compound	*Chemical formula*	*Typical purity (%)*	*Applications*
Tantalum aluminides	$TaAl_3$ Ta_3Al	99.5 na	Aerospace, automotive and turbine parts, and chemical production equipment
Tantalum borides	TaB TaB_2	99.5 99.5	Diffusion barriers in silicon semiconductors, films to harden cutting tools, neutron-absorbing coatings, and advanced ceramics
Tantalum bromides	$TaBr_3$ $TaBr_4$ $TaBr_5$	na na 99.9	na na na
Tantalum carbides	TaC $TaC_{0.88}$	99.0 – 99.5 99.0 – 99.5	Hard-metal and cemented-carbide high-temperature cutting and drilling tools
Tantalum chlorides	$TaCl_3$ $TaCl_4$ $TaCl_5$	na na 99.99	na na Electronics, optics, and catalytic applications
Tantalum ethoxide	$Ta(OC_2H_5)_5$	99.99	Production of tantalum oxide films for optical and semiconductor applications
Tantalum fluorides	TaF_3 TaF_5	99.9 99.9	Anti-reflective and low refractive index optical coatings
Tantalum hafnium carbide	Ta_4HfC_5	99.0	One of the most refractory substances known (melting point 4215°C). High-temperature cutting applications
Tantalum hydride	Ta_2H	na	na
Tantalum iodides	TaI_4 TaI_5	99.9 99.9	na na
Tantalum nitride	TaN	99.5	Thin film TaN resistors and advanced ceramics
Tantalum oxalates	$TaO(C_2O_4)_3$ $TaO(OH)(C_2O_4)_2.H_2O$	na na	Catalytic applications, electroceramics, and capacitors
Tantalum oxides	TaO TaO_2 Ta_2O_5	na na 99.5	Optical systems, ferroelectric properties, optical coatings, dielectrics, film capacitors and semiconductors, and ceramic and catalytic applications
Tantalum phosphide	TaP	na	na
Tantalum selenide	$TaSe_2$	99.9	na
Tantalum silicides	$TaSi_2$ Ta_5Si_3	99.5 – 99.95 99.5 – 99.95	Bipolar transistors and other semiconductor devices and optical properties
Tantalum sulfide	TaS	99.9	Lubricant film on bearings and moving parts
Tantalum telluride	$TaTe_2$	99.8	Lubricant film
Potassium fluorotantalate	K_2TaF_7	98.0	Production of tantalum metal

SOURCES: H. C. Starck (2002); Espi Metals (2002); Stanford Materials Corporation (2002); Goodfellow (2002); Reade Advanced Materials (2002); WebElements (2002); RND Korea (2002); Wilshire Chemical Co. Inc. (2002); Accumet Materials Co. (2002); Cerac Inc. (2002); Process Materials (2002)

NOTE: na not available

Chapter 8

Industrial applications

Electronic applications

Tantalum capacitors

Since 1994, demand for tantalum in the electronics industry has increased by about 15%, making it the largest consumer of tantalum and accounting for about 65% of total demand in 2002. Within this industry, the greatest demand is for tantalum capacitors, with annual production being measured in billions of units (Fig. 35).

Tantalum capacitors are used in many electronic devices such as mobile phones (about 35% of total production), personal computers (PCs), especially laptop PCs, pagers, video cameras, TV remote-control units, photocopiers and fax machines, electronic game processors, smoke detectors, and electronic control systems in automobiles. In industry, tantalum capacitors are used in communication equipment, bar code scanners, security systems, commercial computer systems and ancillary equipment, and instruments and control systems for aircraft, ships, weapons, and missiles.

Tantalum capacitors are devices that regulate the flow of electricity within an integrated circuit. In this situation, capacitors store small electrical charges that can be rapidly discharged as required. The fast response time buffers the capacitor's circuit from any inconsistency in the distribution of power. This is vital for the high-speed operation of digital circuitry (Fig. 36).

In a tantalum capacitor, the core consists of porous tantalum-metal powder surrounded by a thin dielectric insulating layer of Ta_2O_5. The oxide is coated by successive layers of manganese dioxide, graphite, a silver conductive layer, and a solder cap. A tantalum wire is inserted in the core at one end and to the cap at the other (Fig. 37).

In these devices, the capacitance value is proportional to the surface area of the capacitor's plates, the purity of the tantalum powder, and the thickness of the Ta_2O_5 dielectric layer. Tantalum capacitors have a very large surface area and high dielectric constant, properties that give them the highest capacitance per unit volume of any capacitors. Accordingly, larger capacitance values can be obtained with a corresponding increase in efficiency and reduction in size by incorporating them into microcircuits. For example, tantalum's superior efficiency makes it possible to replace a 100 microfarad aluminium capacitor by a vastly smaller 10 microfarad tantalum type. In this way it is possible to achieve substantial size reduction and at the same time optimize power dissipation capability in microcircuits. Tantalum capacitors are also renown for their wide temperature operating range (-55–125°C), enhanced frequency characteristics, operational reliability, and long shelf-life.

Throughout the world there are about 26 tantalum capacitor manufacturers, with most of the larger manufacturers having production plants in a number of countries. There are five major producers in the USA, Japan, and Germany. The US manufacturers are the Kemet Corporation, the world's largest manufacturer of solid tantalum capacitors (Kemet Corporation, 2002); the AVX Corporation, makers of the world's smallest tantalum capacitor (Gill, 2002); and Vishay Intertechnology, specializing in the manufacture of small components required for mobile phones, communication equipment, and military electronic devices (Vishay Intertechnology, 2002). Other major manufacturers are the NEC Tantalum Corporation in Japan and EPCOS in Germany.

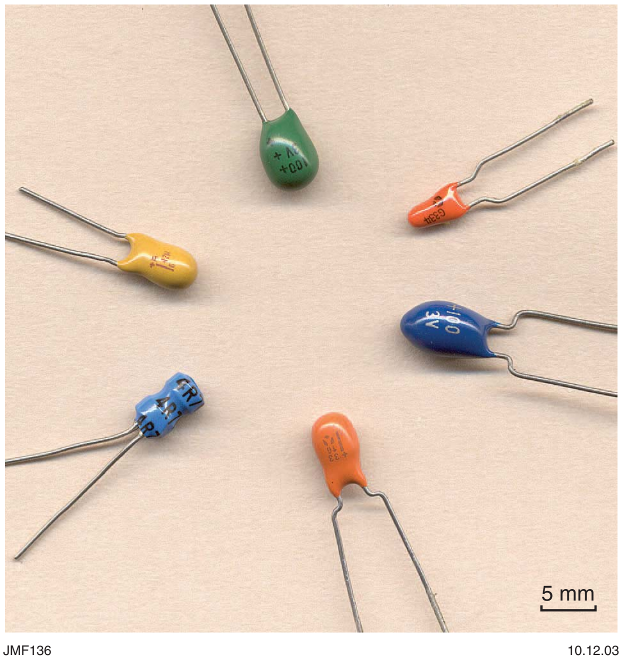

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Figure 35. Tantalum capacitors

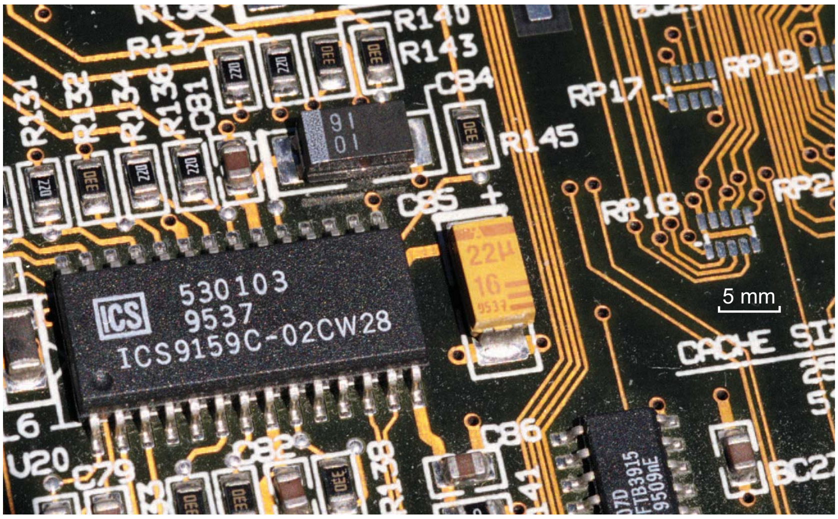

Figure 36. Tantalum capacitor incorporated in a computer circuit. The capacitor (yellow, centre) rapidly discharges small electrical charges to regulate power distribution around the integrated circuit chip (left centre)

Other large Japanese producers are Matsushita EIC, Hitachi AIC, Matsuo Electric, and Nichicon Tantalum Corporation. Smaller manufacturers include Samsung EMCO in Korea, Shenzhen Capacitor in China, numerous Japanese companies, and others located in China, Taiwan, Korea, India, Vietnam, and the Russian Federation (Zogbi, 2002).

Tantalum capacitors are sold around the world to numerous corporations producing electronic equipment employing microcircuitry for use in controlling the operation of each device. Some of the larger producers (especially in Japan and Korea) retain a proportion of their capacitor production for use in their own electronic product production divisions.

Other electronic devices

Other tantalum oxide devices

Other important electronic devices using tantalum oxide are rectifiers (especially for use with railway signals), PC memory chips and processors, and surface acoustic wave filters. In large-scale integrated circuits, thin tantalum oxide films are employed as gate insulators to maintain very low circuit leakage. Methods have also been developed to deposit tantalum oxide films over large areas using tantalum ethoxide in the low-pressure chemical-vapour deposition process for the manufacture of metal-oxide semiconductor (MOS) memory devices, and dynamic random-access memory (DRAM) chips.

Tantalum nitride resistors

Tantalum nitride thin-film resistors have been developed for use in microcircuits due to their improved heat dissipation and power handling capability, particularly at higher frequencies of up to 6 gigahertz compared to 1 gigahertz for other types of film resistors. The excellent temperature stability and reliability of these resistors makes them suitable for use in automotive, telecommunication, computer, medical, and military electronic devices, and in industrial process control, particularly in temperature-sensing devices.

Car airbag igniter

Tantalum has an important life-saving role in the automotive industry where thin-film tantalum-nitride

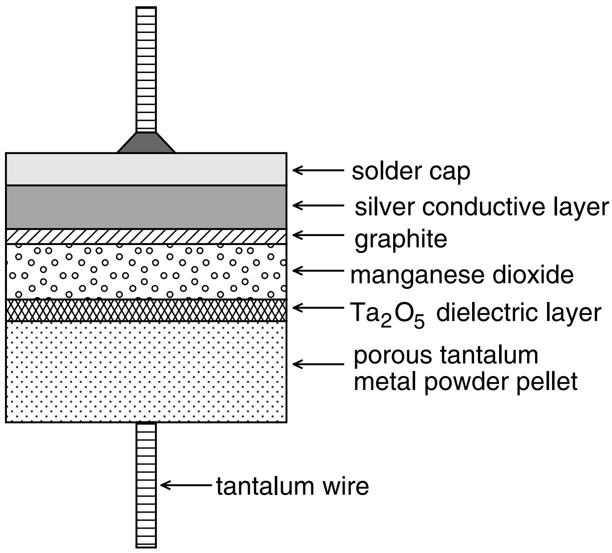

Figure 37. Schematic diagram of a tantalum capacitor. The diagram shows successive layers from the inner porous tantalum metal-powder pellet to the outer solder cap (after Cabot Corporation, 2002c)

igniter chips are used in vehicles as airbag igniters. In this application, a tantalum-nitride resistive element film is mounted on an alumina ceramic body ensuring a robust and highly reliable ignition source. Within milliseconds of a vehicle collision, an electrical current is applied to the igniter causing the tantalum nitride film to heat up extremely rapidly. This ignites the primer charge in the airbag initiator, thus activating the gas generator that inflates the airbag (TT Electronics, 2003).

Tantalum silicide semiconductor devices

Currently, new applications are also being found for tantalum silicides in gallium-arsenate bipolar transistors, and silicon semiconductor devices.

Gettering applications for tantalum in vacuum tubes

Gettering is the ability of a number of elements and oxides to collect free gases by absorption, adsorption, and occlusion. The gas-absorbing metals tantalum, niobium, and zirconium in the form of sheets, wires or powders are known as 'bulk getters'. To acquire the gettering state, the metals must first be heated to operating temperatures of 300–1600°C. Tantalum has long been recognized by electronic vacuum-tube manufacturers as having excellent gettering properties that are used to absorb deleterious gases and maintain a high vacuum inside vacuum tubes during operation.

During tube manufacture, tantalum metal is degassed in a high vacuum at temperatures of 1600–2000°C. Once incorporated inside a vacuum tube, degassed tantalum is capable of absorbing gases up to several hundred times its own volume once reheated to its optimum gettering temperature of about 1000°C. The use of solid tantalum wires and plates as gettering elements in vacuum tube anodes is usually restricted to the most expensive vacuum tubes, due to the relatively high cost of tantalum. In all other tube types, tantalum powder is sintered onto tube anodes during degassing in the manufacturing process. Tantalum getters are typically used in medium- to high-powered radio transmitting tubes and other high-power vacuum tubes intended for special applications (Espe et al., 1950).

Chemical and pharmaceutical processing industries

The chemical and pharmaceutical processing industries represent the second-largest consumer group for tantalum after the capacitor industry, and consume a large proportion of the remaining tantalum stocks.

The demand for tantalum in these industries is due to tantalum's almost complete resistance to attack by most acids below 150°C (equivalent properties to glass) and liquid metals up to 1650°C, making it ideal for use in the highly corrosive environments encountered in many chemical processing plants. This benefit is increased when tantalum's excellent thermal conductive properties are also considered, as tantalum has a higher thermal conductivity than nickel alloys, ductile iron, and stainless and high-temperature steels. This property can be employed in these aggressive chemical environments for efficient heat transference in heat exchangers that tend to remain clean as the corrosion-resistant tantalum is not fouled by corrosive chemicals. In industry, these properties are used to provide an efficient, trouble-free operating environment with very low maintenance.

Pure tantalum, although ideally suited for these applications, is usually restricted to specialized small-scale chemical applications, as it is often too expensive for the construction of large-scale processing equipment. However, the use of the pure metal may be justified in applications involving the most aggressive chemical environments where the performance of tantalum alloys is less than satisfactory. In practice, tantalum alloys such as KBI-40 (Table 11) are often used as more cost-effective substitutes in the manufacture of laboratory and chemical processing equipment designed for use in highly corrosive conditions. Another method of overcoming the problem in the manufacture of large-scale processing equipment is by cladding a thin layer of tantalum onto less expensive metals such as steel, stainless steel, and copper for use as internal tantalum claddings, linings, and coatings.

Comparative corrosion data for the chemically resistant refractory metals tantalum, niobium, titanium, and zirconium when exposed to a variety of corrosive industrial chemicals are given in Table 2.

Chemical processing equipment in the chemical and pharmaceutical industries that requires tantalum or tantalum alloys for use in highly corrosive conditions includes:

- Reaction vessels, reactors, and agitators
- Bayonet heaters
- Storage tanks, containers, and receivers
- Valves
- Heat exchangers (shell and tube) and condensers
- Pumps
- Heating and cooling coils
- Multi-walled piping
- Distillation and absorption columns
- U-tubes
- Expansion joints and rupture diaphragms
- Thermowells
- Electrodes
- Spargers
- Protection tubes for thermocouples
- Funnels and orifices
- Parts such as screws, nuts, sleeves, tubes, sealing discs, and flanges.

Industrial tools and processes

A substantial proportion of tantalum usage is directed towards the metal working and industrial processing industries where heat resistance, thermal properties, and strength are required. An important use is for tantalum carbide alloys in specialized cutting tools.

Table 13. Typical impurity levels for tantalum carbide

	Maximum impurity level (%)
Free carbon	0.15
Oxygen	0.03
Aluminium	0.01
Calcium	0.01
Iron	0.01
Silicon	0.01
Titanium	0.01
Tungsten	0.01
Sulfur	0.003
Total impurities	**0.243**

SOURCE: Espi Metals (2002)

Tools for industry

Tantalum compounds, often as composites with other elements, find use in the manufacture of industrial cutting, boring, and processing tools such as extrusion dies, punches, piercing points, boring bars, and equipment used in electroplating processes.

Tantalum carbide

Tantalum carbide (TaC), the third-largest application for tantalum, is one of the hardest man-made substances. It has a melting point of 3880°C and is used for cutting edges of high-speed hard-metal cutting and boring machine tools, as well as wear-resistant machine parts. Physical vapour deposition (PVD) coatings of tantalum carbide less than or equal to 45 μm particle size and 99.8% pure (Table 13) are generally formed by sputtering tantalum metal in an atmosphere of methane or acetylene gas. TaC coatings may also be deposited on cutting or boring equipment, and other parts either by the chemical vapour deposition process, or by electrospark deposition (ESD) where minute molten droplets of tantalum carbide are applied from an electrode contacting the surface of the part and forming a microweld. Computer control of the ESD process causes the microwelds to overlap, forming a complete new surface on the part. The resultant microwelded part is extremely strong and is capable of withstanding thermal and mechanical shock and bending deformation in excess of that provided by any other coating process.

The extreme hardness of tantalum carbide is exploited in its widespread use in industrial cutting tools, teeth for power shovels, bulldozers, and backhoes, and in drill bits used in the construction and mining industries.

Recent advances in TaC technology have resulted in the production of nanocrystalline tantalum carbide that is much harder, wear and erosion resistant, and longer lasting than the conventional larger grained material. This material is used in the production of microdrills with a diameter of 100 μm (less than the diameter of a human hair). This new material's properties have assisted some manufacturers to increase production rates.

Cemented carbide, also known as 'hard metal', is a material that is a composite of various metal carbides in which very small carbide particles (0.5 – 6.0 μm) are cemented into a compact mass using a binder, usually cobalt (5–12%) and/or nickel. The powder mixtures are pressed in a die to form the required shape before sintering in a furnace at 1400–1500°C. During sintering the cobalt melts and attaches to the carbide particles, forming an extremely hard three-dimensional network upon cooling. Following the sintering process, the hard metal is usually ground to correct size specifications prior to setting on tool cutting faces. An example of a hard-metal composite is 73.5% tungsten carbide, 10.5% tantalum carbide, 7.0% titanium carbide, and 9.0% cobalt binder. This type of hard metal may be used for turning, boring, and grooving steel and alloyed cast iron. Cemented carbides are renown for their toughness, strength, and resistance to abrasion, deflation, and corrosion over a wide range of operating temperatures.

In recent years, researchers in the United States have produced a tantalum carbide – graphite composite material reputed to be one of the hardest substances ever developed, with a melting point of 3738°C.

Tantalum boride

Tantalum boride (TaB_2) coatings deposited by PVD onto industrial metal-cutting tools and dies are effective in extending their useful life by up to five times, which translates to faster throughput and less downtime in manufacturing processes.

Steel industry

Tantalum's property of high thermal conductivity is applied during steel fabrication where tantalum heat-transfer units are used to efficiently remove heat during the steel pickling process.

Textile industry

Due to its strength and wear-resistant properties, tantalum spinnerets are supplied to the textile industry for the manufacture of rayon and other synthetic fibres.

Aerospace industry

In the aerospace industry, sheet metal tantalum is used in jet engines to protect fuel lines from fires. However, it is tantalum's properties of a high melting point, strength at high temperatures, and resistance to corrosion that are incorporated into the 'super alloys' vital to this industry. These super alloys are combinations of tantalum in various ratios with one or more of the following metals — nickel, chromium, tungsten, iron, molybdenum, cobalt, and niobium. In jet engines, the super alloys used in the manufacture of turbine blades consist mostly of nickel and chromium with lesser quantities of iron, tantalum (1.5 – 12%), molybdenum, and niobium (Table 11). They are designed to operate at temperatures between 850 and 1700°C generated by the hot gases emitted from the engine's combustion chamber (Fig. 38). This super-alloy technology is also applied in the manufacture of blades for gas turbines used in contemporary power stations.

Tantalum is also used to strengthen cobalt-based super alloys for stationary inlet vanes and jet engine components. Super alloys using tantalum are used in aerospace structures and other engine components such as hot-gas valves and engine skirts.

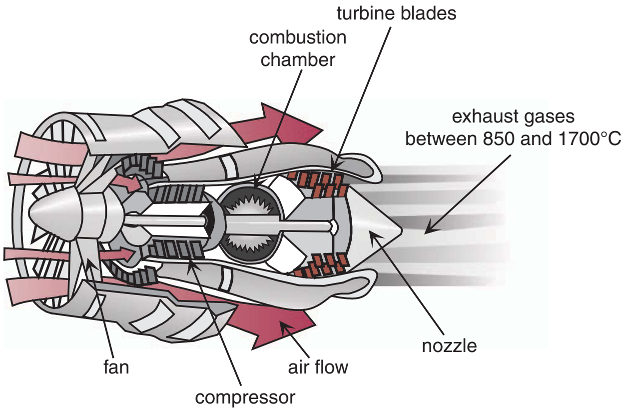

Figure 38. Cross section of a jet engine, showing the location of the turbine. The turbine is fitted with blades made of a nickel–chromium–iron–molybdenum–tantalum–niobium composite alloy designed for efficient and reliable operation at temperatures between 850 and 1700°C (modified from NASA, 2002)

Medicine and dentistry applications

Tantalum and specifically designed tantalum alloys are biologically compatible with the human body. Since they are completely non-reactive and non-irritating with body tissues or fluids, and the body's immune system makes no attempt at rejection, these metals have become invaluable as prosthetic devices and surgical repair parts for bone, tissue, and dental applications. Currently, tantalum implants find many applications in artificial body replacement parts as follows:

- Implants such as artificial joints, especially hip replacements and cranial plates;
- Tantalum implants for use in the repair of human bones (e.g. screws, strips, staples, and plates), or as surgical sutures in the form of foil or wires to connect torn nerves, and woven gauze to bind up abdominal muscles;
- Dental implants made of tantalum have been in use for over 50 years;
- Tantalum retinal implants used by ophthalmic surgeons in eye surgery.

A porous tantalum biomaterial has been recently developed for use as a bone surface coating or as a full-scale bone implant. The porous tantalum structure is manufactured by chemical vapour deposition of tantalum onto a vitreous carbon three-dimensional porous matrix. The resultant strong, permeable material, which can be formed into complex shapes, has a porosity of 75–80%, an average pore size of 0.4 – 0.5 mm diameter, and a modulus of elasticity of 3 GPa. It has been demonstrated that after implantation the porous structure fills rapidly with new bone material produced by the body and ultimately a new bone structure forms over the implant (Bobyn et al., 2001). This new technology has the potential to radically improve artificial joint surgery, currently estimated at over 200 000 replacements per annum worldwide.

As well as implants, tantalum and specially designed alloys are used in the manufacture of strong, chemically inert surgical tools and accessories for bone repair and internal stitching, and also in tools for dental procedures.

Because of their reliability, tantalum capacitors are used in heart pacemakers, insulin pumps, defibrillators, hearing aids, and epilepsy support devices, making these appliances durable, long lasting, and trouble free.

Optical industry

Tantalum pentoxide is applied as thin coatings on glass lenses to increase the refractive index of the glass. This allows lenses to be made thinner, as well as improving lens refracting properties from the near ultra violet (UV at 350 nm) to the infra-red (IR at approximately 8 µm) spectral bands. Hard, scratch resistant layers of the oxide are applied to the glass using sputtering techniques. These coatings find applications in aerial camera lenses and night-vision goggles.

Because the refractive index of tantalum pentoxide is greater than two at below 300 nm wavelength, it is sometimes combined in multi-layers with silicon dioxide for use in UV laser applications.

Refractory industry

Due to its high melting point and other useful thermal properties, tantalum vacuum-furnace linings, heating elements, fixtures and susceptors, and also boats and trays for the transfer of molten metal, are manufactured for use in the refractory industry. More recently, a tantalum–rhenium alloy has been developed (Table 11). In refractory applications this alloy demonstrates excellent mechanical properties up to 3000°C.

Other gettering applications for tantalum

Tantalum's superior gettering ability is also applied in the removal of deleterious gases in ultra-high vacuum furnaces. In this situation, tantalum removes potential contaminants of niobium, niobium alloys, and titanium during heat treatment operations. Tantalum getters are also used in some gas purification systems.

Military applications

Tantalum is used in the area of high-penetration ballistics, as well as in components for missile technology such as heat shields, hot gas valves, and exhaust systems for rocket motors.

High-temperature shape-memory alloy

In the late 1990s, the United States Naval Research Laboratory developed a tantalum–ruthenium ($Ta_{50}Ru_{50}$) high-temperature shape-memory alloy (Table 11). Alloys of this type can be bent, compressed, or deformed and are then capable of recovering their original shape by heating. At 1120°C, the $Ta_{50}Ru_{50}$ alloy has the highest shape-memory transition temperature of any alloy of this type. This material has potential applications in sensors, actuators, fasteners, and vibration dampeners in high-temperature environments in aircraft and automobile engines, and in the chemical processing industry (Naval Research Laboratory, 2002).

Nuclear industry

In the nuclear industry tantalum metal is used in heat shields. Due to its neutron absorption properties, tantalum is employed as radiation shielding, and tantalum boride films find application as neutron-absorbing layers on nuclear-reactor fuel pellets.

Pure tantalum or tantalum-lined crucibles are used to reduce, melt, and cast uranium or plutonium for nuclear applications. The crucibles are specially designed to avoid nuclear criticality, being cylindrical with a height to diameter ratio greater than or equal to two, and typically 30 cm high with a 14 cm diameter. Other types of tantalum containers are used for the transfer of radioactive waste.

Standard weights

It has been recognized that pure tantalum metal is more resistant than platinum to many corrosive chemicals. Accordingly, tantalum has largely replaced platinum in standard laboratory weights.

Catalyst

Tantalum is used in the rubber industry as a catalyst for the synthesis of butadiene (artificial rubber) in the manufacture of items such as car tyres.

X-ray images

Tantalum is combined with yttrium in the manufacture of yttrium tantalate phosphor that is used to produce a brighter screen image and at the same time reduces the patient's exposure to X-ray radiation.

Substitutes

Substitution of tantalum generally takes place during times of high demand that cause price escalations and shortages of supply. This situation occurred during price surges in 1979–80, 1988, and 2000–01. In 1979–80, the price increase actually caused a decrease in tantalum use through recycling and substitution. In some electronic products tantalum capacitors were replaced by aluminium substitutes (Hunziker, 2001).

In 2000–01, the situation reoccurred during the massive escalation in demand for mobile communications and computer equipment, when spot prices leaped from A$157/kg (US$39.50/lb) to greater than A$770/kg (US$180/lb). It is apparent that during periods of high prices and shortages in supply manufacturers begin to look seriously at substitute materials for tantalum.

Many materials can be substituted for tantalum; however, usually with less effective results. In the electronics industry niobium, aluminium, and ceramics may be substituted for tantalum for capacitors in certain specific applications. In metal cutting, boring, and abrading applications niobium may be substituted for tantalum in tantalum carbide. Niobium, glass, platinum, titanium, and zirconium may be used as tantalum substitutes in corrosion-resistant equipment in the chemical and pharmaceutical industries. Finally, in high-temperature applications, tantalum may be replaced by niobium, hafnium, iridium, molybdenum, rhenium, and tungsten (Cunningham, 2002).

With reference to the substitution of tantalum capacitors in the electronics industry, it appears that potential substitutes are usually capable of covering only discrete parts of the operating range of tantalum capacitors in terms of voltage, capacitance, and temperature. To date, much research has gone into the search for suitable substitutes, and in mid-2001 the NEC Corporation launched the first polymer-type niobium capacitor.

Other corporations have also been involved in research into the production of ceramic, aluminium polymer, and niobium capacitors. Key factors in this process are the market's need for product miniaturization coupled with high performance. Research into the use of niobium capacitors has revealed that whereas niobium has a dielectric constant three times higher than tantalum, twice as much niobium per unit volume is required to provide the same effective charge. In addition, niobium capacitors cannot be used reliably in excess of 10 volts DC, and they become unstable at temperatures greater than 105°C, whereas tantalum capacitors can be used in certain applications up to almost 100 volts DC and are capable of reliable operation at temperatures greater than 125°C. In 2000, it was estimated that niobium has the potential to eventually replace about 10% of the tantalum capacitor market (Angus & Ross plc, 2002a).

Chapter 9

Global reserves, production, and market trends

Global ore reserves

Data relating to defined global tantalum ore reserves must be regarded as approximate only. In a number of countries, there is some confusion as to what constitutes a defined reserve meeting the equivalent of the reserve criteria defined by the Australian JORC Code (JORC, 1999), as distinct from what are probably loosely defined tantalum resources in many cases.

Countries with defined tantalum reserves include Australia, with the Greenbushes and Wodgina deposits in Western Australia having at least 75% of global reserves at 152.1 Mt at 0.028% Ta_2O_5 and containing almost 43 140 t (95.1 Mlb) Ta_2O_5. Other countries with defined global resources are Canada with 8% from the TANCO mine in Manitoba, and 5% from Brazil. All other countries are estimated to contain global reserves totalling 12% (Cutifani, 2001).

These reserve estimates are likely to change in time with the proper definition of other tantalum reserves, especially in parts of Africa, China, and the Russian Federation. However, it should be noted that often there is a valid reason as to why some apparently large tantalum resources have not been exploited in recent years. These reasons include political risk, the prevailing tantalum economic situation, mining and infrastructure costs, ore contamination, and mining and metallurgy problems resulting in poor Ta_2O_5 recovery.

Sources of raw materials and production

Between 1998 and 2001, world production of contained tantalum oxide increased threefold from 598 t (1.318 Mlb) in 1998 to a peak value of 1863 t (4.107 Mlb) in 1999, and declined to 1504 t (3.317 Mlb) in 2000 (Mining Journal, 2001).

Currently, the world's largest single producer is Sons of Gwalia from its two mines in Western Australia at Greenbushes in the southwest of the State, and Wodgina in the Pilbara district in the northwest of the State. In early 2000, these two deposits produced about 26% of the world's high-grade tantalum concentrate. By the end of 2001, this figure had increased to close to 45% of world output of about 806 tpa (1.78 Mlb), assisted by the two smaller Western Australian producers of Haddington Resources at the Bald Hill mine and Tantalum Australia at the Dalgaranga mine (Department of Mineral and Petroleum Resources, 2001).

It is estimated that another 26% of the world's supply emanates from Africa. Currently, the largest single African mine is at Kenticha in Ethiopia. This mine produces about 68 tpa (0.15 Mlb/annum). Other countries with substantial tantalum production are the Democratic Republic of the Congo, Rwanda, Burundi, and Uganda. It is estimated that the coltan (columbite–tantalite) trade from these countries fluctuates between 136 and 227 tpa (0.3 – 0.5 Mlb/annum; Linden, 2000). Other major African tantalum-producing countries include Mozambique, Nigeria, and Zimbabwe. Tantalum is also refined from tin slags at Jos in central Nigeria.

Brazil is the next largest producer, with about 14% of global production from its mines at Pitinga and Nazareno. Other major producing countries are China with about 3.3% mainly from the Yichun mine, together with lesser amounts from Nanping. Canada also produces almost 3% of the total, with all production coming from the TANCO mine at Bernic Lake, Manitoba.

Outside of China, Thailand is the only other significant tantalum producer in Asia. In Thailand, Thaisarco processes tin slags derived from Thailand, Malaysia, and Indonesia. In 2000, the company produced greater than 45 t (0.1 Mlb) of tantalum concentrate from slags containing about 10% Ta_2O_5. In former years, annual production was in excess of 227 t (0.5 Mlb). This decline in production is attributed to the reduction in offshore tin-dredging operations in these countries (Linden, 2000).

Other sources of tantalum raw materials are synthetics, and the tantalum resources held at the US Defense National Stockpile Center managed by the US Defense Logistics Agency. These sources are discussed below. Sources of global raw materials and concentrate production are shown in Figures 39 and 40.

Synthetics

Tantalum-bearing synthetic concentrates are produced from old accumulations of low-grade tin–tantalum slags from Southeast Asia, especially Malaysia, and some countries in Africa. The production of synthetics still plays an important role in the global supply of tantalum (Fig. 41), but is declining annually due to the increasing scarcity of available slags and the rising cost of processing lower grade material. Korinek (2000) estimated that in 2000 the annual production of tantalum from tin slags was less than 45 tpa (0.1 Mlb per annum). The preparation of synthetic concentrates is carried out in Germany by two companies, one of which is H. C. Starck, reputed to be the world's largest tantalum producer (Passive Component Industry, 2000).

US Defense National Stockpile Center

It is estimated that the United States has tantalum resources of about 1500 t (3.31 Mlb) contained in a number of deposits. However, these deposits are mostly low grade, and some are mineralogically complex, making most deposits currently uneconomic to mine.

As a buffer against its reliance on imported supplies of tantalum as a strategic metal, the US has created a tantalum reserve supply at the Defense National Stockpile Center (DNSC), operated by the US Defense Logistics Agency. At the end of the 2001 fiscal year, the DNSC's tantalum inventory totalled 979 t (2.16 Mlb) comprising mainly tantalum minerals plus smaller quantities of tantalum carbide powder, capacitor-grade tantalum metal powder, tantalum ingots, and tantalum oxide (Cunningham, 2002).

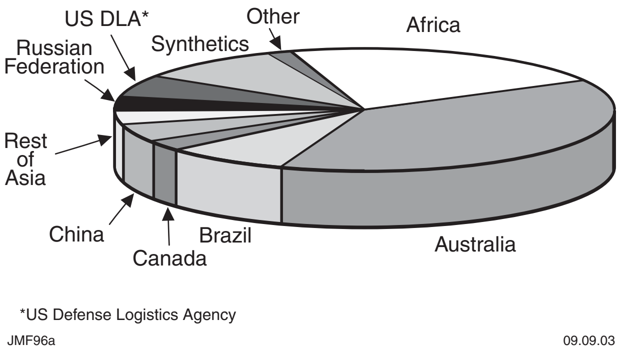

Figure 39. Major sources of tantalum raw material supply in 2000 (modified from data courtesy Sons of Gwalia Ltd)

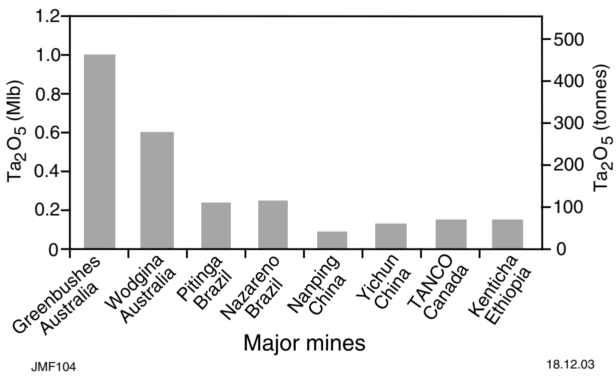

Figure 40. Ta_2O_5 concentrate production from major mines for the 2000–01 fiscal year (modified from Sons of Gwalia Ltd, 2002b)

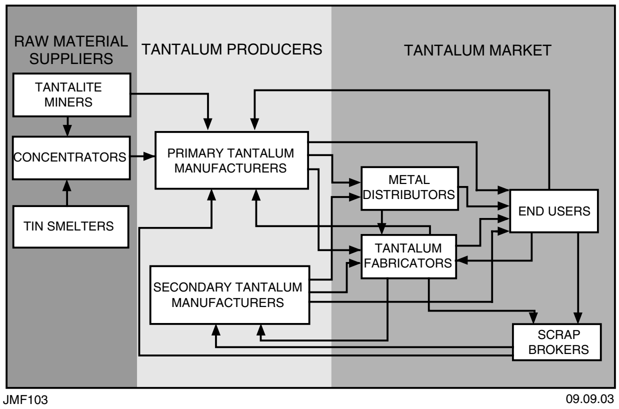

Figure 41. The international tantalum supply chain. Diagram shows the movement of Ta_2O_5 concentrate from mines and smelters to primary and secondary tantalum manufacturers, and the supply of products to the international tantalum market (modified from Michaluk, 2000b)

From this stockpile, the DNSC proposes maximum disposal limits for future fiscal years. In the 2001 fiscal year, 54 t (0.12 Mlb) of various tantalum materials were sold for US$38.4 million. Spot prices for these materials are set according to the prevailing demand. For example, in 2000 spot prices for DNSC high-grade material reached a high of US$455/lb.

The international supply chain

Figure 41 shows how tantalum and tantalum products are moved through the international supply chain. Starting with the raw material suppliers, mainly tantalite mining companies and the tin–tantalum slag refiners, most of the material passes through various concentrators, emerging as tantalum concentrate between 10–60% Ta_2O_5. From here, most concentrate is exported to other countries to primary tantalum manufacturers for the processing of tantalum ingots and the manufacture of metallurgical- and capacitor-grade tantalum powders.

These basic materials are then sold via tantalum metal distributors either to tantalum-fabricating industries or directly to end-users such as tantalum capacitor manufacturers, and the manufacturers of tantalum chemicals, tantalum carbide, and super alloys. The tantalum metal fabricators transform tantalum metal into primary products such as wire, sheet, and pipes. Primary metal products are then onsold to the secondary manufacturers who use the materials to make tantalum equipment for industry such as wear-resistant tools and machine parts, and corrosion-resistant components for use in the chemical industry.

Recycling of scrap

Another factor in the supply chain is the recycling of tantalum scrap, which represents a substantial proportion of available tantalum metal. Cunningham (2002) estimated that for the United States in 2001, tantalum-scrap recycling constituted about 20% of total tantalum consumption. In the supply chain, tantalum scrap is moved both from metal fabricators and end-users back to primary manufacturers for remelting, or to secondary manufacturers for reuse in tantalum metal products.

Tantalum scrap is classified into two groups:

- ‘Old scrap’ that includes metal articles that have been discarded after serving a useful purpose such as tantalum-containing cemented carbides, and super alloys;
- ‘New scrap’ is produced during the manufacture of metals and articles and includes all defective finished or semi-finished articles destined for reworking. Examples of new scrap include borings, castings, clippings, skims, and turnings.

In the US in 1998, about 300 t (0.66 Mlb) of tantalum contained in old scrap was produced. Of this, only about 90 t (0.20 Mlb), valued at US$8.0 million, was recycled or reused. The recycling efficiency was about 35% and the recycling rate about 21%. In the same year, new tantalum scrap reused was about 120 t or 0.26 Mlb (Cunningham, 1998).

Global consumption by industry

Tantalum consumption by industry can be broadly classified into five categories:

- Electronics — tantalum capacitors
- Tantalum mill products and wire
- Metal cutting — tantalum carbide
- Tantalum chemicals
- ‘Super alloys’ incorporating tantalum.

Figure 42 shows the relative trends in the market share of each of these groups over the period 1993–2000. Whereas the usage for chemicals, carbides, and mill products has remained relatively static over the eight-year period, the demand for capacitor-grade Ta_2O_5 for the electronics industry has grown by almost three times, and the demand for super alloy-grade tantalum has increased by a factor of six.

Sons of Gwalia has estimated that in 2000 tantalum usage in the electronics industry dominated the market with a 61% share. This was followed by mill products at about 15%, super alloys at 10%, metal-cutting carbides at 8%, and tantalum chemicals at 6% (Cutifani, 2001).

World prices for tantalum

Most common metals such as copper and nickel are bought and sold on international metal markets such as the London Metal Exchange. Unlike these metals, tantalum is not traded on a central market, but rather through a series of dealers around the world who establish spot prices depending on prevailing demand for each new

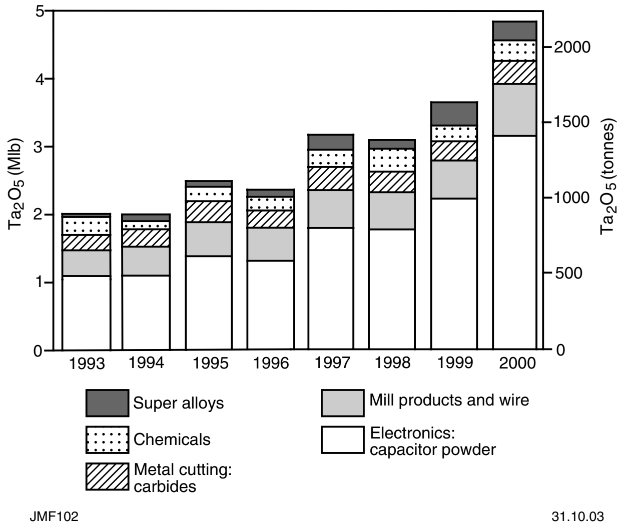

Figure 42. Global tantalum consumption by industry 1993–2000 (modified from Angus & Ross plc, 2002b)

transaction. Therefore, there are no published prices for tantalum metal, metal powder, chemicals, alloys, and fabricated tantalum products. Instead, prices are privately negotiated, based largely on product specifications and volume required.

In order to avoid fluctuating spot prices, major tantalum-mining companies such as Sons of Gwalia establish long-term, fixed price, take or pay contracts for their entire production with their customers. These contracts have the effect of masking the true price of a substantial proportion of tantalum traded (about 26% of the total in the case of Western Australia) through their strict confidentiality clauses that prevent any disclosure of price.

The need to establish stable prices through the use of take or pay contracts is borne out by fluctuating Ta_2O_5 concentrate spot prices over the last 25 years. Over this period, there have been three substantial price surges, roughly one every 10 years. The first of these occurred in 1979–80 when prices jumped from A$74/kg (US$39.50/lb) to greater than A$187/kg (US$100/lb). This was largely brought about by a period of shortages of supply and panic buying.

Again in 1988 the tantalum price almost doubled from A$67/kg (US$26/lb) to A$129/kg (US$50/lb) over a short period. This was attributed to a depletion of tantalum inventories caused by a sudden increase in demand for tantalum concentrate.

The situation reoccurred in 2000–01 during the recent escalation in demand for mobile communications and computer equipment when spot prices leaped from A$157/kg (US$39.50/lb) to greater than A$770/kg (US$180/lb). Once again, the price spiral was short-lived, with prices crashing to less than A$428/kg (US$100/lb) in the second half of 2001, and by mid-2002 reaching a low of A$86–107/kg (US$20–25/lb). Fluctuations in spot prices since 1959 are shown in Figure 43.

Over the past 50 years, price spirals in spot prices for tantalum can be attributed to tantalum, a comparatively rare metal with easily disrupted supply routes, being subject to shortages of supply caused by inventory hoarding and panic buying. Conversely, substitution of other metals, and slackening demand largely due to oversupply, have led to price contractions. For these reasons, the tantalum spot price does not necessarily parallel world economic cycles in a similar fashion to other metals such as copper. However, tantalum's price has been demonstrated to be much more volatile than other metals, for example in times of recession tantalum's price may be 2–10 times more volatile than that of copper (Hunziker, 2001).

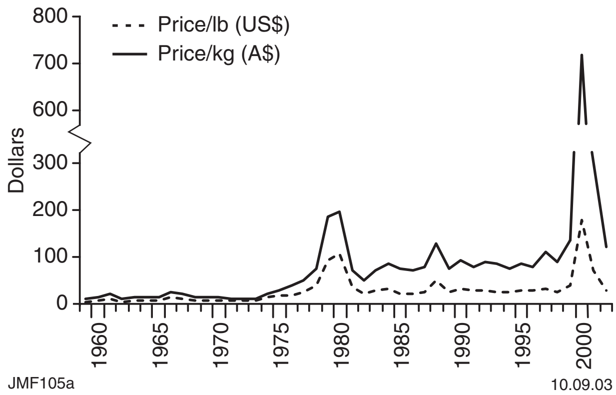

Figure 43. Year-end spot prices for Ta_2O_5 concentrate 1959–2002 (modified from Simandl, 2001)

Western Australian production and value

Since the commencement of record keeping approximately 100 years ago, tantalum production in Western Australia has totalled 10 990 t (24.23 Mlb) to the end of 2001. During this period, tantalum production hit a record of 925 t (2.01 Mlb) in 1992, and there were three major price spikes in 1980, 1995, and 2001. These surges in production and price are attributed to periods of increased demand for tantalum. In 2001, production peaked at 806 t (1.78 Mlb) valued at A$179.3 million (Fig. 44).

Value of production differs from international spot pricing in that the value of Ta_2O_5 concentrate is assessed by the Western Australian Government based on its estimated free on board (f.o.b.) value for the purpose of annual royalty calculation. As a result, the concentrate values tend to be significantly lower than spot prices obtained on the international market, but nevertheless tend to mirror international spot price movements. The total value of production of tantalite in the State is estimated at A$699 046 434.

Marketing

Despite the significant drop in global demand for tantalum metal from an all-time high of 2268 t (5.0 Mlb) in 2000 to 1560 t (3.44 Mlb) in 2001, the marketing of tantalum products continues in the traditional areas of mill products (14%), metal cutting (7%), and chemicals (5%) on a relatively constant basis. A growing area of tantalum sales is in the super alloy industry (10%) where tantalum is in increasing demand for incorporation into high-temperature super alloys in the manufacture of turbine blades for jet aircraft engines and power station turbines. In this role tantalum improves the structural integrity of the blades, thus enabling turbines to operate at higher temperatures and resulting in increased fuel efficiency.

Notwithstanding the reduction in global demand for tantalum powder by the electronics industry in 2001, it remains by far the biggest market sector for the tantalum industry, with consumption reaching 65% of total demand in the 2001–02 fiscal year. Every year billions of tantalum capacitors are manufactured to satisfy the demand by communications, computer, audio-visual, automotive, and electronic services industries. Fastest growing products from these industries include mobile phones, laptop computers, and domestic audio-visual entertainment equipment (especially playstations and video cameras). For example, in 2000 more than 400 million mobile phones were sold around the world and it was estimated that worldwide sales would reach 550 million units in 2002 (Avalon Ventures Ltd, 2002a).

The largest consumers of tantalum capacitors are the Sony and Motorola Corporations, which each consumed about two billion units in 2000. The Matsushita–Panasonic Corporation is another major consumer. However, this company also manufactures tantalum capacitors and diverts 45% of its capacitor production into the manufacture of its own consumer goods (Passive Component Industry, 2002). Major industrial consumers of tantalum capacitors are shown in Table 14.

New products involving the use of tantalum are continuously under development to satisfy contemporary demands by the electronics market. For example, new

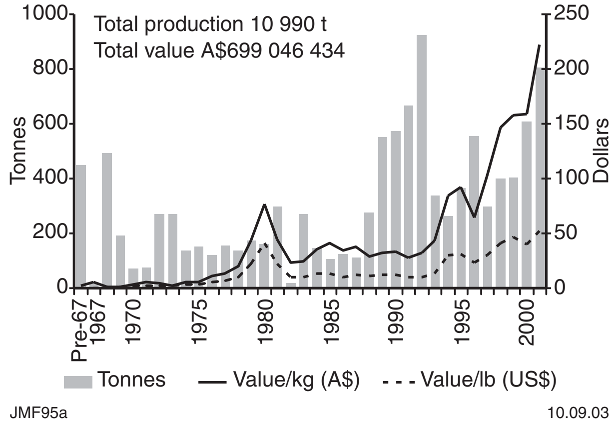

Figure 44. Annual production and estimated f.o.b. value (dollars of the day) of tantalite mined in Western Australia (Department of Mineral and Petroleum Resources, 2001)

Table 14. Major industrial consumers of tantalum capacitors in 2000–01

Communications industry		*Computer industry*		*Audio-visual equipment*	*Automotive industry*	*Electronic manufacturing services*
Mobile phones	*Infrastructure*	*Motherboards*	*Disk drives*			
Nokia	Nortel	IBM	Seagate	Sony	Robert Bosch	Solectron
Motorola	Cisco	Dell	Western Digital	Hitachi	Visteon	Sanmina–SCI
Ericsson	Lucent	Compaq	Quantum	NEC	Delphi	Celestica
Panasonic	Alcatel	Hewlett Packard	Panasonic	Panasonic	Nippondenso	Flextronics
Samsung	Ericsson	Apple	IBM	Nintendo	Marelli	Jabil
Siemens	Siemens	Fujitsu	Others	Sega	VDO	Others
Sony	Nokia	Toshiba	–	Others	Others	–
Sagem	Others	Intel	–	–	–	–
Kyocera	–	Others	–	–	–	–
Others	–	–	–	–	–	–

SOURCE: Passive Component Industry (2002)

developments include tantalum wafers to prevent molecular 'bleeding' in the silicon–copper join in high-performance integrated circuits, and tantalum wave filters in wireless communications networks (Sons of Gwalia Ltd, 2002b).

Economic outlook

In June 2000 Sons of Gwalia, the world's largest tantalum producer, renegotiated its five-year take or pay contracts with its two principal customers, the Cabot Corporation from the US and H. C. Starck in Germany. Over the period until 2005, the company contracted to sell to its customers an average of 998 tpa (2.2 Mlb per annum) of tantalum concentrates.

However, the substantial fall in global demand for tantalum in late 2001 to 1560 t (3.44 Mlb), together with a corresponding crash in spot prices reaching a low of A$86/kg (US$20/lb) by mid-2002, had a major effect on all tantalum producers including Sons of Gwalia. In response to the downturn in demand, in December 2002 the company introduced a program of operating efficiencies by reducing production of lower grade material from the Greenbushes mine by 159 t (0.35 Mlb) to 340 t (0.75 Mlb) in 2003. At the same time, production from the higher grade Wodgina mine was to be increased to 680 t (1.5 Mlb) to achieve the reduced total output of between 998 and 1043 t (2.2 – 2.3 Mlb) for 2003 (The West Australian, 2002).

At the same time, Sons of Gwalia announced the shelving of the underground development at the Greenbushes mine in order to cut capital spending in a struggling tantalum market. It is expected that the development of the underground decline can be restarted as soon as demand for tantalum increases.

It is recognized that the recent significant fall in demand was driven by a reduction in demand by the electronics and communications industries, followed by a period of tantalum inventory corrections throughout the supply chain. These inventory corrections were necessary as it subsequently became apparent that after the boom period of 2000 substantial hoarding of tantalum had occurred in many areas of the supply chain, and it has taken until the end of 2002 for these inventory bottlenecks to disperse (Sons of Gwalia Ltd, 2002a).

Despite current low spot prices for tantalum concentrates, Sons of Gwalia expects that with the end of the tantalum-inventory oversupply situation, combined with a reduced supply of coltan coming out of central Africa, 2003 should see a return to positive Ta_2O_5 concentrate exports. During this period and up until December 2005, the company has increased its market share and at the same time is protected from any further weakness in tantalum demand and price through its fixed price take or pay contracts. Other Western Australian producers are also directly or indirectly protected in a similar fashion from these demand and price variations.

With the probable return to increased shipments of tantalum concentrates in 2003, given that no further inventory bottlenecks occur in the supply chain in the short term, it is expected that the expanding electronics and communications industries should provide the necessary impetus for a resurgence in demand, together with increased prices for this high-tech metal, within a few years.

At present the electronics industry is producing about 29 billion tantalum capacitors per annum. It is estimated that capacitor demand will grow at 9–10% each year until 2005. This accelerating trend is driven by increasing demand for miniaturized passive electronic components, especially tantalum capacitors for applications in increasingly smaller packages. This includes new-generation computer memory chips and processors, and new electronic applications in the automotive industry. This trend in the electronics industry towards component miniaturization has the potential to be a major tantalum consumer of the future (Hunziker, 2002).

Chapter 10

International tantalum resources — exploration and mining

This chapter examines the tantalum resources outside of Australia, not just in terms of resource size in any particular country, but more particularly in relation to the surge of exploration activity that has occurred in various countries in recent years. This surge was very largely due to the substantial but short-lived jump in world tantalum prices from late 2000 to early 2001. It is likely that the increased tantalum exploration over this period has provided valuable information that has contributed to a much more accurate picture of global tantalum resources.

Canada, Alaska, and Greenland

During the above mentioned period, the most rapid increase in tantalum exploration occurred in Canada, Alaska, and Greenland, with the most intense area of exploration being centred on granitic rare-metal pegmatites intruding Archaean greenstones in the central Canadian states of Manitoba and Ontario. Other areas of increased interest included carbonatite-hosted tantalum deposits in British Columbia and Greenland, and syenite- and nepheline syenite-hosted deposits in the Northwest Territories and in Greenland. Locations for the region's tantalum mine, deposits, prospects, and exploration province are shown in Figure 45.

Canada

In recent years, over 30 tantalum deposits and prospects have been subject to intensive exploration. Despite all the intensive exploration programs and good grades obtained at some prospects, to date Canada's original tantalum deposit at Bernic Lake, Manitoba remains as the country's only producing mine. Detailed summaries of the principal Canadian tantalum prospects, deposits, and mine are given in Tables 15–19.

British Columbia

In British Columbia, tantalum mineralization appears to be almost entirely related to carbonatite-style intrusions, with about 10 such deposits or prospects being recorded in mountainous terrain in the southeast of the state.

The two most notable tantalum exploration sites are the Verity–Paradise deposit and Fir prospect, both of which are about 30 km north-northeast of Blue River in southeastern British Columbia. Here, large carbonatite sill-like structures have intruded Neoproterozoic gneissic metasedimentary rocks. The carbonatites are rich in tantalum–niobium minerals, mainly pyrochlore and ferrocolumbite. The Verity carbonatite has a strike length of 7 km and is up to 70 m thick, whereas the Fir carbonatite is an almost flat-lying body, 400 m long and up to 75 m wide.

Both exploration sites are owned by Commerce Resources Corporation. Inferred resources at the Verity deposit have been estimated at 3.06 Mt at 0.020% Ta_2O_5, 0.065% Nb_2O_5, and 3.2% P_2O_5, whereas the Fir prospect has yielded drillhole grades of up to 0.032% Ta_2O_5 over 8.2 m (McCrea, 2001). Commerce Resources is endeavouring to develop a beneficiation process to extract tantalum and niobium from the pyrochlore mineralization.

A summary of the principal tantalum deposit and prospects in British Columbia is given in Table 15.

Manitoba and Ontario

These central Canadian states have been the focus of the most intensive tantalum exploration programs in the country in recent years, with at least 21 prospects being investigated out of a total of about 30 known granitic rare-metal pegmatites. The main area of interest is in the Kenora region of southwest Ontario, and extending into southeast Manitoba in the area around Bernic Lake. Other areas with considerable potential include the Northern Superior Province of central-eastern Manitoba and extending into Ontario (Fig. 45). This exploration area covering about 20 000 km^2 contains at least five prospective tantalum-bearing pegmatites. Another underexplored area is the Sachigo Province, an area of about 9000 km^2 that surrounds the Pakeagama and Pennock Lake tantalum prospects in central-eastern Ontario.

Throughout Manitoba and Ontario, granitic rare-metal pegmatites are generally hosted by Archaean metasedimentary and metavolcanic rocks of the Kenoran greenstone belts, and are situated in close proximity to numerous peraluminous granites of late Archaean age (2650–2550 Ma; Manitoba Geological Survey, 2002). Pegmatite emplacement is usually controlled by zones of structural weakness such as shear zones. Pegmatites may occur individually, in swarms, or occasionally as stacked

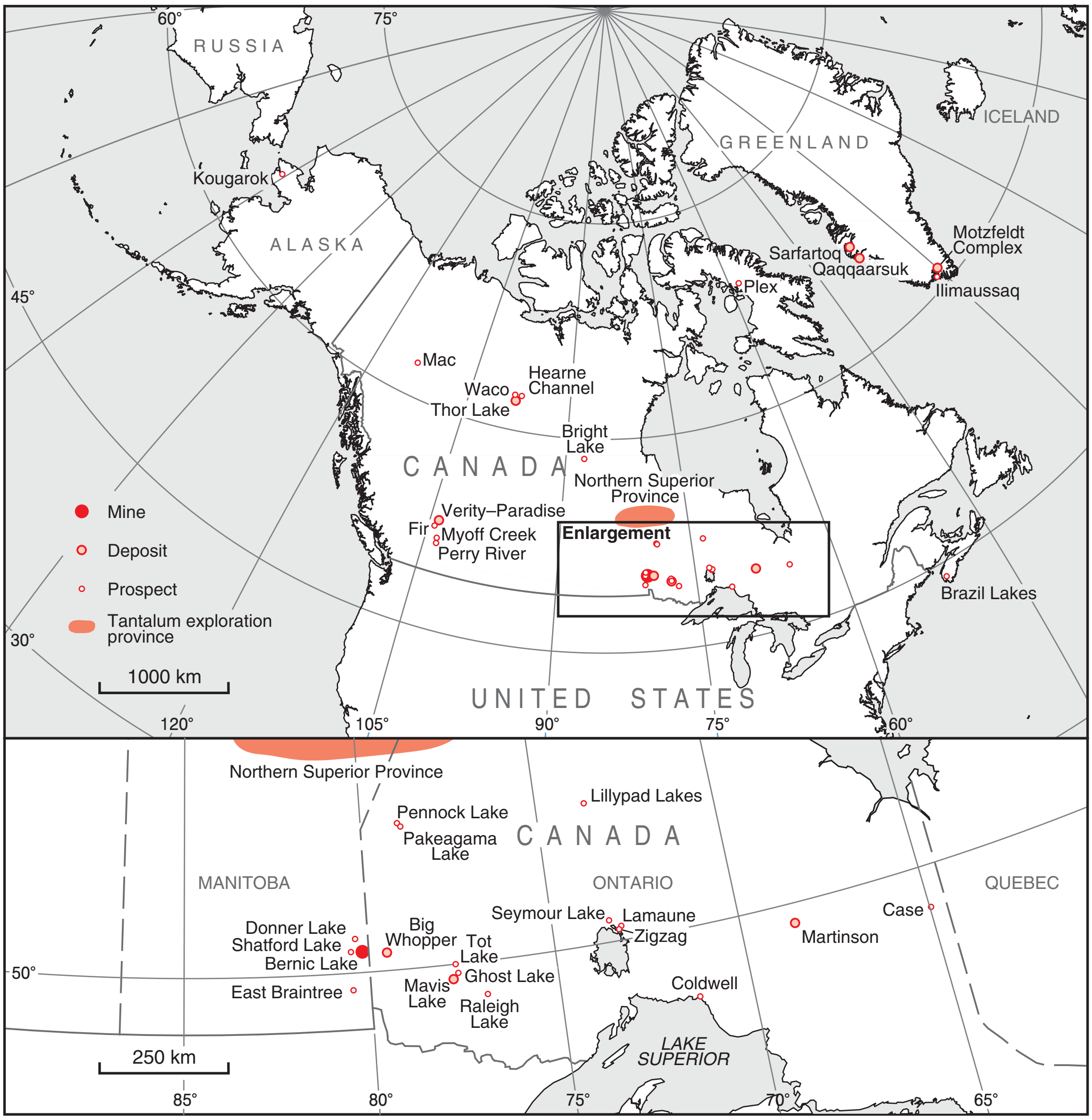

Figure 45. Tantalum mining operations, deposits, prospects, and exploration province in Canada, Alaska, and Greenland

sheets. Discrete associations of mineral assemblages within these pegmatites tend to match Cerny's classification given in Table 8. In general, regional zonation increases with the textural complexity of the pegmatites. As distance from host granites increases, pegmatites tend to exhibit progressive fractionation and rare-element enrichment, often resulting in complex internal zonation patterns.

Many deposits are rich in a wide range of minerals including tantalum–niobium, lithium, caesium, and rubidium. A number of bodies consist of dyke-like pegmatites rich in pollucite (a caesium mineral) or rubellite (a form of tourmaline) and contain high tantalum values commonly of the order of 0.036 – 0.050% Ta_2O_5. The Lillypad Lakes tantalum–caesium prospect in north-central Ontario is a good example of this type. Average Ta_2O_5 grades for the region of about 0.030 – 0.040% (obtained from drilling or grab sampling) appear to be on a par with many established tantalum deposits around the world. However, since no resource figures have been published for these prospects, it would appear that many may have resources too small for development in the current climate of low tantalum prices.

Apart from the dominant granitic rare-metal pegmatites in the region, there are two other types of tantalum deposit under investigation. The first of these is the Coldwell peralkaline granite–syenite–metasomatite prospect in central-southern Ontario. In this prospect, tantalum mineralization occurs in altered syenites of the Proterozoic Coldwell Alkaline Intrusive Complex. Tantalum minerals include aeschynite, columbite–tantalite, and pyrochlore, with grab-sample values of 0.03% Ta_2O_5 being recovered.

Table 15. Significant tantalum mineralization in British Columbia, Canada

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Fir prospect	25 km north-notheast of Blue River	Commerce Resources	Carbonatite	Ferrocolumbite, pyrochlore	Apatite, richterite, U enrichment	Beforsite	Drillhole grades over 8.2 m: 0.032% Ta_2O_5, 0.140% Nb_2O_5, 3.15% P_2O_5
Myoff Creek prospect	55 km northwest of Revelstoke	Cross Lake Minerals	Carbonatite	Niobium and tantalum mineralization	REE enrichment	Carbonatite	0.137% Nb_2O_5, 0.0034% Ta_2O_5 (channel samples)
Perry River prospect	30 km northwest of Revelstoke	Commerce Resources	Carbonatite	Columbite–tantalite, pyrochlore	Apatite, molybdenite, pyrite, sphalerite, chalcopyrite, monazite, REE enrichment	Sovite	Not available
Verity–Paradise deposit	35 km north-northeast of Blue River	Commerce Resources	Carbonatite	Pyrochlore, ferrocolumbite, fersmite	Apatite, magnetite, vermiculite; REE, U, and Zr enrichment	Beforsite, sovite	Inferred resources: 3.06 Mt at 0.020% Ta_2O_5, 0.065% Nb_2O_5, 3.2% P_2O_5

SOURCES: Pell and Hora (1990); Commerce Resources Corp. (2002)

The Martinson carbonatite deposit is located in central-eastern Ontario. With resources of 113 Mt averaging 21.4% P_2O_5, it was intended that this deposit would be developed as a phosphate fertilizer resource in future years. However, it has been reported that the deposit contains a zone with significant concentrations of Nb_2O_5 and Ta_2O_5 (The Northern Miner, 2001).

A summary of the principal tantalum prospects, deposits, and mining activities in Manitoba and Ontario is given in Tables 16 and 17.

Bernic Lake tantalum–lithium–caesium mine

At Bernic Lake in southeast Manitoba, an extensive pegmatite has intruded Archaean metasedimentary and metavolcanic rocks of the Bird River greenstone belt. At this location, the Tantalum Mining Corp. of Canada Limited (TANCO), a wholly owned subsidiary of the Cabot Corporation, operates Canada's only tantalum–lithium–caesium mining operation. The mine was originally established in 1929 as a short-lived operation to mine and process tin from the local area. However, it was not until 1969 that the mine resumed operations as a tantalum mine. Fully fledged operations only began in 1984 when TANCO began to mine its spodumene resource for lithium, which today is its major product together with tantalum, caesium, and rubidium ores that are present in discrete zones.

The shallow underground mine, accessed by a 20° decline, is mined by room and pillar method. The mine has a complex mineralogy with over 80 minerals present. Major minerals include spodumene, amblygonite, wodginite, microlite, pollucite, lepidolite, and K-feldspars. Underground mining operations are shown in Figure 46.

In 2001, the Bernic Lake operation produced about 94 t of Ta_2O_5 concentrate, up about 35% on the previous year's production of about 70 t (Cunningham, 2001).

Northwest Territories

There are four tantalum exploration sites in the Northwest Territories. Three of these are located in the Yellowknife area of the Great Slave Lake region.

The site that has attracted the most attention in recent years is the Thor Lake deposit, about 60 km southeast of Yellowknife. This peralkaline granite–syenite–metasomatite-style deposit is one of five mineralized zones forming part of the Blatchford Lake Alkaline Complex. The mineralization is hosted in an altered syenitic pegmatite – nepheline syenite body thought to be a late-stage derivative of the alkaline complex.

Previous exploration by Placer Development outlined an indicated resource of 70 Mt at 0.03% Ta_2O_5 and 0.4% Nb_2O_5 at Thor Lake. The deposit is currently under investigation by Navigator Exploration Corp. The tantalum mineralization in this deposit was originally found to be too fine-grained to be concentrated by conventional gravity-separation techniques. Navigator is investigating a newly developed flotation process that has the potential to produce good recoveries of high-grade tantalum concentrate.

Table 16. Significant tantalum mineralization in Manitoba, Canada

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Bernic Lake mine	180 km east-northeast of Winnapeg	Tantalum Mining Corp. of Canada (TANCO)	Granitic rare-metal pegmatite	Columbite–tantalite group, ferrotapiolite, wodginite group, ixiolite group, strüverite, microlite, simpsonite	Spodumene, amblygonite, pollucite, lepidolite, K-feldspar, cassiterite; Be, Rb, and Ga enrichment	Pegmatite	Reserves pre-production (1991): 2.1 Mt at 0.216% Ta_2O_5 and 7.3 Mt at 2.76% Li_2O
Donner Lake prospect	25 km north-northwest of the TANCO mine, Bernic Lake	Kermode Resources	Granitic rare-metal pegmatite	Columbite–tantalite group, ferrotapiolite, wodginite group, ixiolite group, strüverite, microlite, simpsonite	Li, Rb, and Cs enrichment	Pegmatite	Ta_2O_5 grades: Main Dyke: <0.067% South Dyke: 0.025 – 0.055% (grab samples)
East Braintree prospect	130 km east of Winnapeg	Avalon Ventures	Granitic rare-metal pegmatite	Tantalum oxide minerals	Cleavelandite (albite), lepidolite, tourmaline, Cs and Rb enrichment	Pegmatite	Ta_2O_5 grades from 0.029% over 44 m to 0.051% over 1.65 m
Northern Superior Province prospects: Cross Lake, Gods Lake, Red Cross Lake, Red Sucker Lake, Ponask Lake	Manitoba–Ontario, 520–600 km north-northeast of Winnapeg		Granitic rare-metal pegmatite	Columbite–tantalite group, wodginite, microlite	Albite, spodumene, tourmaline, purpurite, petalite, beryl, apatite, pollucite, amblygonite, molybdenite, bismuthinite, lepidolite, zinnwaldite, cassiterite	Pegmatite	Not available
Shatford Lake prospect	6 km southwest of Bernic Lake	Avalon Ventures	Granitic rare-metal pegmatite	Columbite–tantalite group, ferrotapiolite, wodginite group, ixiolite group, strüverite, microlite, simpsonite	Li, Cs, and Rb enrichment	Pegmatite	Not available

SOURCES: Manitoba Geological Survey (2002); Avalon Ventures Ltd (2002b); Kermode Resources Ltd (2002)

Table 17. Significant tantalum mineralization in Ontario, Canada

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Big Whopper deposit	Separation Lake, 60 km north of Kenora	Avalon Ventures	Granitic rare-metal pegmatite	Columbite–tantalite (secondary ore)	Li-feldspars and petalite (primary ore), lepidolite, Rb enrichment, spodumene, cassiterite, spessartine	Pegmatite intruding mafic metavolcanic rocks	Indicated and inferred resources: 13.8 Mt at 1.34% Li_2O, 0.34% Rb_2O, and 0.007% Ta_2O_5
Case prospect	75 km east of Cochrane	Platinova A/S	Granitic rare-metal pegmatite	Columbite–tantalite	Not available	Pegmatite	Ta_2O_5 grades: 0.024% over 8.8 m to 0.035% over 4.5 m
Coldwell prospect	Near Marathon	Avalon Ventures	Peralkaline granite/syenite/ metasomatite	Pyrochlore, columbite–tantalite, aeschynite	Rutile, bastnaesite, and other REE minerals	Pegmatite and altered syenite	Ta_2O_5 grade: 0.03% (grab samples)
Ghost Lake prospect	11 km north-northeast of Dryden	Houston Lake Mining	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Lithium and tin mineralization, tourmaline	Pegmatite	0.019% Ta_2O_5, 0.012% Sn
Lamaune prospect	220 km north-northeast of Thunder Bay	Platinova A/S	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Lithium mineralization	Pegmatite	Ta_2O_5 grade (average): 0.021%
Lillypad Lakes prospect	150 km northeast of Pickle Lake	Avalon Ventures	Granitic rare-metal pegmatite	Microlite	Pollucite, rubellite (tourmaline)	Pegmatite (Cs enriched) intruding mafic volcanics	Ta_2O_5 grades: 0.036% over 24 .0 m to 0.05% over 8.0 m
Martinson deposit	Near Hearst	MCK Mining Corporation	Carbonatite	Significant Ta–Nb secondary mineralization	Apatite, magnetite	Carbonatite	Resources: 113 Mt at 21.4% P_2O_5
Mavis Lake deposit	10 km east of Dryden	New Claymore Resources	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Lithium mineralization; Be, W, and Cs enrichment	Pegmatite	Resources: 0.5 Mt LiO_2
Pakeagama Lake prospect	170 km north of Red Lake	Houston Lake Mining	Granitic rare-metal pegmatite	Columbite–tantalite group, ferrotapiolite, stibiotantalite, wodginite, microlite	Cassiterite, lepidolite, spodumene, pollucite, tourmaline	Pegmatite (Cs, Rb, and Li enriched)	Ta_2O_5 grade: 0.034% over 11 m (channel sample)
Pennock Lake prospect	185 km north of Red Lake	Kermode Resources	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Lithium mineralization	Pegmatite	Not available
Raleigh Lake prospect	20 km east of Ignace	Avalon Ventures	Granitic rare-metal pegmatite	Columbite–tantalite group, microlite	Li, Rb, and Cs enrichment	Pegmatite intruding mafic metavolcanic rocks	Ta_2O_5 grades: 0.011% over 5.4 m to 0.027% over 2.0 m

Table 17. (continued)

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Seymour Lake prospect	45 km northeast of Armstrong	Linear Resources	Granitic rare-metal pegmatite	Columbite–tantalite	Spodumene, lepidolite, beryl, albite; Rb and Cs enrichment	Pegmatite	Ta_2O_5 average grades: 0.037% over 13.4 m (2 drillholes), 0.043% (>50 channel samples)
Tot Lake prospect	33 km northeast of Dryden	Platinova A/S	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Lepidolite, Cs enrichment, garnet	Pegmatite intruding metavolcanic rocks	Ta_2O_5 grade: 0.036% over 4.1 m
Zigzag prospect	55 km east of Armstrong	Platinova A/S	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Lithium mineralization	Pegmatite	Ta_2O_5 grades: 0.37% over 1.0 m; 0.05% over 8.4 m (channel samples)

SOURCES: Avalon Ventures Ltd (2002c); Houston Lake Mining Inc. (2002); Linear Resources Inc. (2002); Platinova A/S (2002a)

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Figure 46. Underground operations at the TANCO tantalum–lithium–caesium mine at Bernic Lake, Manitoba (photo courtesy Sons of Gwalia Ltd)

Another company, Platinova A/S, is currently exploring a block adjacent to Navigator's Thor Lake property.

Elsewhere in the Yellowknife area are two granitic rare-metal pegmatite tantalum prospects. About 100 km east of Yellowknife, Navigator are investigating the Hearne Channel prospect where fractionated pegmatite dykes have yielded grab samples ranging from 0.07 to 1.30% Ta_2O_5. At Waco, 50 km east of Yellowknife, Platinova A/S is investigating a tantalum-bearing pegmatite swarm.

In the remote Mackenzie Mountains located in the eastern Northwest Territories, the War Eagle Mining Company is investigating the Mac prospect that comprises about 25 pegmatite bodies forming part of the Little Nahanni Pegmatite Group, an albite–spodumene dyke complex that intrudes Proterozoic metasediments of the Selwyn Basin. The Mac prospect pegmatites form a discrete swarm within a 200 m-wide zone extending over a strike length of about 5.5 km. Grab samples from the central part of the dyke system have yielded 0.053 – 0.080% Ta_2O_5 and 1.82 – 2.15% Sn.

A summary of the principal tantalum deposit and prospects in the Northwest Territories is given in Table 18.

Nova Scotia, Saskatchewan, and Nunavit Territory

There is one granitic rare-metal pegmatite prospect reported from each of these widely scattered states. The

Table 18. Significant tantalum mineralization in the Northwest Territories, Canada

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Hearne Channel prospect	100 km east of Yellowknife	Navigator Exploration Corp.	Granitic rare-metal pegmatite	Mineralization style similar to Bernic Lake	–	Pegmatite	Ta_2O_5 grades: 0.07 – 1.3% (grab samples)
Mac prospect	250 km north of Watson Lake (B.C.)	War Eagle Mining/ Strategic Metals	Granitic rare-metal pegmatite	Columbite–tantalite, stiverite	Cassiterite, spodumene, albite, K-feldspar	Pegmatite	Ta_2O_5 grades: 0.053% – 0.080%; 1.82 – 2.15% Sn (grab samples)
Thor Lake deposit	60 km southeast of Yellowknife	Navigator Exploration Corp. (Platinova A/S exploring on adjacent property)	Peralkaline granite/ syenite/ metasomatite	Unspecified tantalum and niobium mineralization	Zr and REE enrichment, nepheline	Syenitic pegmatite/ syenite	Indicated resources: 70 Mt at 0.03% Ta_2O_5 and 0.4% Nb_2O_5
Waco prospect	50 km east of Yellowknife	Platinova A/S	?Granitic rare-metal pegmatite	Tantalite	–	Pegmatite	Not available

SOURCES: Navigator Exploration Corp. (2002a); Platinova A/S (2002b)

most interesting of these properties is the Plex prospect located on remote Baffin Island in the Nunavit Territory. Platinova A/S is currently reinvestigating a series of zoned rare-metal pegmatites containing columbite–tantalite that were originally examined in 1980 by Cominco. At that time Cominco reported high tantalum values associated with muscovite-rich segregations in various internal pegmatite zones. A summary of the principal tantalum deposit and prospects in these states is given in Table 19.

Alaska

Currently, Alaska is the only state of the USA with significant tantalum mineralization. The Kougarok prospect is situated on the Seward Peninsula in western Alaska, about 112 km north-northeast of Nome. This prospect is a rare-metal (Li–F) granite similar to the Yichun rare-metal apogranite tantalum deposit in China (see **China** later in this chapter). The Kougarok prospect comprises a tabular lithium–fluorine granite plug buried 200–400 m below the surface. The plug, which is 100–150 m thick with a surface area of about 1.2 × 1.0 km, may have been the feeder system to an overlying magmatic–hydrothermal system containing tin–tantalum mineralized greisens, the target of the present exploration program.

The deposit is being jointly explored by Navigator Exploration Corp. and Chapleau Resources. Drillhole results have returned grades up to 0.043% Ta_2O_5 over 31.5 m. The Kougarok prospect is summarized in Table 20.

Greenland

There are four significant tantalum deposits located in western and southern Greenland. The Qaqqaarsuk and Sarfartoq deposits in western Greenland, operated by New Millenium Resources, are niobium-rich carbonatite deposits with pyrochlore being the potential ore-bearing mineral. Whereas Qaqqaarsuk contains only minor Ta_2O_5 grades, Sarfartoq has returned some high-value drill intersections for Ta_2O_5 such as 0.146% over 9.0 m.

The Ilimaussaq alkali intrusion (8 × 17 km in size) in southern Greenland, also owned by New Millenium Resources, is an agpaitic nepheline syenite deposit with zircon (0.8 Mt at 6% ZrO_2), rare earths (0.2 Mt at 3% REE), and yttrium oxide (39 000 t at 0.2% Y_2O_5) being the target mineral ores. Tantalum analyses have returned 0.040% Ta.

The deposit with the greatest potential for tantalum in Greenland is situated in the Motzfeldt Complex, in southern Greenland. The deposit is currently being evaluated by Angus & Ross. The Motzfeldt Complex is a major alkaline structure covering an area of 300 km^2 within the Gardar Rift. The main igneous phase of the complex is a ring structure of largely concentric, outward and steeply dipping units mainly composed of peralkaline syenite and nepheline syenite. The oldest outer ring contains the tantalum–niobium mineralization. Tantalum is present in the mineral pyrochlore in which the Ta

Table 19. Significant tantalum mineralization in Nova Scotia, Saskatchewan, and Nunavit Territory, Canada

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Brazil Lakes prospect	Nova Scotia, 25 km northeast of Yarmouth	Waseco Resources	Granitic rare-metal pegmatite	Columbite–tantalite	Spodumene, cassiterite, beryl, albite, zircon, microcline, Rb enrichment	Pegmatite intruding amphibolite and quartzite	Ta_2O_5 grades: 0.014% over 6.19 m to 0.011% over 8.44 m
Bright Lake prospect	North-central Saskatchewan	Leader Mining International	Granitic rare-metal pegmatite	Unspecified tantalum mineralization	Li, Rb, and Cs enrichment	Pegmatite	0.0147% Ta_2O_5, 0.070% Sn (grab samples)
Plex prospect	Nunavit Territory, Baffin Island, 350 km east of Hall Beach	Platinova A/S	Granitic rare-metal pegmatite	Columbite–tantalite	Muscovite	Pegmatite	Not available

SOURCE: Platinova A/S (2002c)

Table 20. Significant tantalum mineralization in Alaska, USA

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Kougarok prospect	Seward Peninsula, 112 km north-northeast of Nome	Navigator Exploration Corp./ Chapleau Resources	Rare-metal (Li–F) granite	Columbite–tantalite, ?microlite	Cassiterite, albite, zinnwaldite, ?lepidolite, pyrrhotite, arsenopyrite, wolframite, fluorite, Bi and Ag enrichment	Albitized and greisenized granite	Ta_2O_5 grades: 0.024% over 115.1 m to 0.043% over 31.5 m

SOURCE: Navigator Exploration Corp. (2002b) concentration level ranges from 1.3 to 1.8%, and the Ta:Nb ratio varies from 1:8 to 1:50. The Ta:Nb ratio also varies vertically in the deposit, with the highest tantalum values occurring towards the base. Ta:Nb ratios are usually higher in altered syenites compared to peralkaline microsyenites.

Inferred resources at Motzfeldt were originally estimated at 50 Mt at 0.03 – 0.10% Ta_2O_5 and 130 Mt at 0.04 – 1.00% Nb_2O_5. However, recent exploration by Angus & Ross in 2001 at Locality 4 within the Motzfeldt Complex has located enriched pyrochlore zones in an altered syenite unit, resulting in preliminary estimates of a high-grade resource of 15 Mt at greater than 0.050% Ta_2O_5 and 0.600% Nb_2O_5, plus a lower grade resource of more than 20 Mt at greater than 0.030% Ta_2O_5 and 0.400% Nb_2O_5. The company is also evaluating methods of producing a concentrate of about 35% Ta_2O_5 and Nb_2O_5 at a 65% recovery rate from the high-grade ore (Angus & Ross plc, 2002c).

A summary of the principal tantalum deposits in Greenland is given in Table 21.

Africa

Tantalum mineralization has been reported from at least 17 countries in Africa. Central African countries such as the Democratic Republic of the Congo, Uganda, Burundi, and Rwanda have been significant suppliers of tantalum concentrates for at least 40 years, with all production from alluvial and eluvial deposits produced by artisanal mining groups and prospectors. Other countries producing significant quantities of tantalum include Nigeria, Ethiopia, and Zimbabwe. Mining operations were recently started in Namibia and Mozambique. Minor tantalum production has been reported from countries such as Zambia, Gabon, South Africa, Niger, and the Ivory Coast; however, details relating to deposits and production levels are extremely limited.

Recently an Australian company, Gippsland Limited, identified a 40 Mt tantalite deposit at Abu Dabab in Egypt's Eastern Desert (Gippsland Limited, 2002a). Deposits of tantalum, niobium, tin, and tungsten have also been discovered in the Tibesti Mountains of northern Chad.

Over most of Africa, almost all known tantalum deposits and prospects appear to be related to granitic rare-metal pegmatites or their regolith derivatives, such as deeply weathered deposits formed in situ, or transported eluvial and alluvial placer deposits. The few exceptions to this are tantalum mineralization within rare-metal apogranite intrusions in the area around Abu Dabab in Egypt, and in peralkaline granites in several areas of central Nigeria.

Throughout western, central, and southern Africa there are numerous intrusions of younger phase late Archaean or early Palaeproterozoic granites, similar to younger Archaean granite suites in cratonic areas of Western Australia and central Canada. In many places, late-phase rare-metal pegmatites, ranging from individual bodies to extensive swarms, emanated from these granitic bodies to intrude schists and gneisses of older greenstones.

A summary of the principal tantalum mines, deposits, and prospects in Africa is given in Table 22 and their locations are shown in Figure 47.

Democratic Republic of Congo

Tantalum mineralization is widespread throughout the eastern part of the Democratic Republic of Congo (DRC), being found in Kivu, Maniema, Orientale, and Katanga Provinces. In these areas there are extensive, thick eluvial and alluvial placer deposits of columbite–tantalite (known locally as 'coltan' and containing 10–40% Ta_2O_5) and also cassiterite. For over 40 years, coltan deposits in the region have been mined by artisanal family mining groups and prospectors, with the main centre for collection and distribution being the town of Goma on the country's eastern boundary with Rwanda. The DRC is currently the largest tantalum producer in Africa.

With the outbreak of the second Congolese war in 1998, mining, distribution and sale of coltan came under the control of the Rwandan-backed rebel army holding power in eastern DRC. During 2000 coltan mine production peaked at 130 t, but by 2001 had dropped back to 60 t (Cunningham, 2002). This situation continued for over three years until the withdrawal of the rebel army in mid-2002. It appears that the mining situation in the DRC is now stabilizing despite prevailing low world tantalum prices.

Egypt

In late 2001, Gippsland Limited identified three rare-metal (Li–F) tantalum–tin granite deposits in the Eastern Desert region of Egypt, about 75 km south of the seaport of Quseir. The deposits are hosted in small apogranite stocks up to 400 m in diameter. Estimated Ta_2O_5 resources are Abu Dabab with 39.9 Mt at 0.025%, El Nuweiba with 83 Mt at 0.016%, and Umm Naggat with 25 Mt at 0.015% (Egyptian Geological Survey and Mining Authority, 2002).

The company, which has a 50% joint venture agreement with the Egyptian Government in this project, is currently focusing its attention on the Abu Dabab deposit, with the objective of bringing the project into production in 2004. To buffer against further volatility in the current price of tantalum, the company is also considering producing high-grade feldspar for the ceramic industry from the deposit. It has been estimated that about 0.5 Mtpa of albite and microcline feldspar could be produced in addition to tantalite ore (Industrial Minerals, 2002a).

Ethiopia

Ethiopia is the second largest producer of tantalum in Africa. All production comes from the Kenticha mine, owned by Midroc Ethiopia, about 300 km south of Addis Ababa. The mine produces tantalite ore from deeply weathered pegmatite regolith overlying the rare-metal

Table 21. Significant tantalum mineralization in Greenland

Mine/deposit/ prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Ilimaussaq deposit	South Greenland, 50 km southwest of Narsarsuaq International Airport	New Millennium Resources	Agpaitic nepheline syenite	Unspecified Nb–Ta mineralization	Zircon, REE, sodalite; Y, Hf, Be, U enrichment	Nepheline syenite	Estimated resources: 0.8 Mt at 6% ZrO_2, 0.2 Mt at 3% REE, 39 000 t at 0.2% Y_2O_3, 0.040% Ta, 0.100% Hf
Motzfeldt Complex deposit	South Greenland, 25 km east of Narsarsuaq International Airport	Angus & Ross	Peralkaline granite/ syenite/ metasomatite	Pyrochlore	Thorite, zircon, bastnaesite; REE, U, Th, Mo enrichment	Syenite, nepheline syenite	Inferred resources: 50 Mt at 0.03 – 0.1% Ta_2O_5, 130 Mt at 0.04 – 1.0% Nb_2O_5
Qaqqaarsuk deposit	West Greenland, 160 km north-northwest of Nuuk	New Millennium Resources	Carbonatite	Pyrochlore and betafite (niobium ore with Ta enrichment)	REE enrichment	Carbonatite (sovite), glimmerite, fenite	Indicated resource: 3.5 Mt at 0.5% Nb_2O_5
Sarfartoq deposit	West Greenland, 270 km north-northwest of Nuuk	New Millennium Resources	Carbonatite	Pyrochlore in high-grade niobium-rich ring dykes	–	Carbonatite	Indicated niobium resource: 0.1 Mt at 4.6% Nb_2O_5. Drill intersections: 19.6% Nb_2O_5 and 0.146% Ta_2O_5 over 9 m

SOURCES: Angus & Ross plc (2002c); New Millennium Resources NL (2002)

Table 22. Significant tantalum mineralization in Africa

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Burundi and Rwanda							
Kigali region, Rwanda	Numerous small deposits and workings	Small cooperatives and artisanal miners	Probably placer	Columbite–tantalite (‘coltan’)	–	?Stream sediments	Not available
Democratic Republic of Congo							
Kivu, Maniema, Orientale, Katanga provinces	Numerous eluvial and alluvial deposits and workings	Artisanal miners	Placer	Columbite–tantalite (‘coltan’)	Cassiterite	Soil and stream sediments	Not available
Egypt							
Eastern Desert, 65–90 km south of Quseir (Red Sea)	Abu Dabab deposit	Gippsland Ltd (50%) Egyptian Govt (50%)	Rare-metal (Li–F) granite	Columbite–tantalite	Cassiterite, Na/K-feldspar, tungsten mineralization	Granite	Total resources of 39.9 Mt at: 0.025% Ta_2O_5, 0.012% Nb_2O_5, 0.089% Sn, 0.48 Mt feldspar.
	El Nuweiba deposit		Rare-metal (Li–F) granite	Columbite–tantalite	Tin, tungsten mineralization	Granite	Ta_2O_5 reserves: 83 Mt at 0.0156%.
	Umm Naggat deposit		Rare-metal (Li–F) granite	Columbite–tantalite	Tin, tungsten mineralization	Granite	Ta_2O_5 reserves: 25 Mt at 0.0151%
Equatorial Guinea							
Rio Muni, Acocseng area, 150 km southeast of Bata	Aconibe prospect		Placer, granitic rare-metal pegmatite	Columbite–tantalite	–	Soil, alluvium, pegmatite	Columbite–tantalite placer grades: 3.0–7.5 kg/m^3
	Ayamiken prospect		Placer, granitic rare-metal pegmatite	Columbite–tantalite	–	Soil, alluvium, pegmatite	Not available
Ethiopia							
300 km south of Addis Ababa	Kenticha mine	Midroc Ethiopia	Mineralized, deeply weathered regolith over granitic rare-metal pegmatite	Columbite–tantalite	Quartz, feldspar, kaolin	Regolith materials, pegmatite	Proven low-grade reserves of 116 Mt
Ghana							
100 km northwest of Accra	Akim-Oda prospect	Leo Shield Exploration	Placer derived from granitic rare-metal pegmatite	Columbite–tantalite	–	Stream sediments	Not available
	Anamase prospect				–	–	Not available

Table 22. (continued)

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Mozambique							
Zambezia Province, Alto Ligonha region	Morrua deposit	Cabot Corporation joint venture	Granitic rare-metal pegmatite	–	Quartz, beryl, tourmaline, topaz, kaolin, Cs and Li enrichment	Pegmatite	Reserves: 7.5 Mt at 0.07% Ta_2O_5
	Muriane deposit		Granitic rare-metal pegmatite	Columbite–?tantalite	Quartz, beryl, tourmaline, topaz, kaolin, Cs and Li enrichment	Pegmatite	7.0 Mt at 0.016% Ta_2O_5 (pre-production)
	Marropino deposit		Mineralized, deeply weathered regolith over granitic rare-metal pegmatite	Columbite–?tantalite	Quartz, beryl, tourmaline, topaz, kaolin, Cs and Li enrichment	Regolith materials, pegmatite	21.7 Mt at 0.019% Ta_2O_5
Namibia							
25 km south of Warmbad	Tantalite Valley mine	Tantalite Valley Mining	Granitic rare-metal pegmatite	Columbite–tantalite	Lithium and bismuth mineralization, beryl, mica	Pegmatite	Reserves and resources: 0.74 Mt at 0.043% Ta_2O_5
220 km west-northwest of Windhoek	Sandamap prospect (Erongo area)	Reefton Mining	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite, lithium mineralization, tourmaline	Pegmatite	0.021% Ta_2O_5 (composite drilling samples) and up to 0.045% Ta_2O_5 (soil samples)
250 km northwest of Windhoek	Nainais–Kohero prospect	Rusina Mining and Reefton Mining	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite in cassiterite schist	Not available
Uis area, 290 km northwest of Windhoek	Three Aloes mine	Central African Mining & Exploration, artisanal miners	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, alluvial and eluvial material	Resources: 7.2 Mt at about 0.05% Ta_2O_5
Uis area, 290 km northwest of Windhoek	B1 and C1 Pegmatites prospects	Central African Mining & Exploration, artisanal miners	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Resources: 2.0 Mt at 0.024% Ta_2O_5, 0.094% SnO_2
Uis area, 290 km northwest of Windhoek	Uis slimes dam mine	Central African Mining & Exploration	Reprocessing of tin–tantalum dumps	Columbite–tantalite	Cassiterite	–	Resources: 4 Mt at 0.006% Ta_2O_5, 0.053% Nb_2O_5, 0.33% SnO_2
Strathmore area, 334 km west-northwest of Windhoek	Numerous prospects and small mines	Central African Mining & Exploration, artisanal miners	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite, petalite, beryl, mica	Numerous pegmatites and ?stream sediments	Not available

Table 22. (continued)

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Nigeria							
Jos Plateau, central Nigeria, especially around Jos and Nasarawa	Numerous small deposits and workings	Mainly artisanal miners	Granitic rare-metal pegmatite, peralkaline granite/syenite/metasomatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, stream sediments	Not available
Nasarawa region, 500 km east-northeast of Lagos	Numerous prospects and workings	Columbia River Resources, artisanal miners	Granitic rare-metal pegmatite, peralkaline granite/syenite/metasomatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, stream sediments	Ta_2O_5 grades up to 0.035%
Uganda							
Mainly in southwest and northeast Uganda	Numerous small deposits and workings	Mainly artisanal miners	Granitic rare-metal pegmatite, ?placer	Columbite–tantalite, microlite	Beryl	Pegmatite, ?stream sediments	Not available
290 km west-southwest of Kampala	Nyanga prospect	Uganda Gold Mining	Mineralized, deeply weathered regolith over granitic rare-metal pegmatite	Columbite–tantalite	Beryl, cassiterite, quartz	Regolith materials, pegmatite	Average ore grade: 31.54% Ta_2O_5 and 30.56% Nb_2O_5
Zimbabwe							
Mainly in eastern and central western Zimbabwe	Numerous small deposits and workings, especially around Kamativi	Small cooperatives and artisanal miners	Granitic rare-metal pegmatite, mine dumps, placer	Columbite–tantalite	Cassiterite	Pegmatite, stream sediments	Not available
420 km west-southwest of Harare	Kamativi mine	Allied Mining Investments	Reprocessing of tin–tantalum dumps	Columbite–tantalite	Cassiterite	–	Not available
Sutswe area, 170 km north-northeast of Harare	Eagle mine and Donsa mine	Central African Mining & Exploration	Granitic rare-metal pegmatite, regolith	Columbite–tantalite, microlite	Beryl, quartz, spodumene, muscovite, albite, microcline	Pegmatite, eluvial material in soil	Resources: Eagle: 0.61 Mt at 0.034% Ta_2O_5. Donsa: 1.62 Mt at 0.025% Ta_2O_5
Sutswe area, 170 km northeast of Harare	Dove 14 mine	Central African Mining & Exploration	Granitic rare-metal pegmatite	Columbite–tantalite	Beryl, quartz, muscovite, albite	Pegmatite	Resource: 0.65 Mt at 0.044% Ta_2O_5
Rusambo area, 185 km north-northeast of Harare	Anomalous tantalite prospects	Central African Mining & Exploration	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Beryl	Pegmatite, stream sediments	Not available
Shamva area, 80 km northeast of Harare	Wanroo deposit		?Granitic rare-metal pegmatite	Microlite	–	Pegmatite	0.129 Mt at 0.07% Ta_2O_5

SOURCES: Africa (general) — U.S. Geological Survey (2002); Minmet Ozmine (2002a); MBendi (2002)
Egypt — Gippsland Ltd (2002b); Egyptian Geological Survey and Mining Authority (2002)
Namibia and Zimbabwe — Central African Mining and Exploration Co. plc (2002)

Figure 47. Tantalum mining provinces, mining operations, deposits, and prospects in Africa and Saudi Arabia

pegmatite body at depth, and from adjacent eluvial deposits. In 2000 production peaked at about 54.4 tpa. Once mining of the unconsolidated regolith ore has been completed, attention will have to be focused on mining the underlying hard-rock ore. Initial indications are that the hard-rock tantalum resources could be significant, with grades probably about 0.020% Ta_2O_5 and available resources capable of producing between 90 and 226 tpa (Linden, 2000).

Mozambique

In Mozambique, tantalum mineralization is confined to the northwest region of Alto Ligonha in the Zambezia Province. In this region complex, zoned granitic rare-metal pegmatites have been mined for tantalite for many years and more recently three major deposits have been identified. The first of these is the Morrua deposit, once the largest tantalite producer in Mozambique, with estimated reserves of 7.5 Mt at up to 0.07% Ta_2O_5. This deposit is currently being re-evaluated by the Cabot Corporation in a joint venture arrangement. It is possible that this deposit could be redeveloped to produce 200 tpa of tantalite; however, significant infrastructure costs would be involved. The remaining deposits at Muriane and Marropino are estimated to contain reserves and resources of 7.0 Mt at 0.016% and 21.7 Mt at 0.019% Ta_2O_5 respectively. At Marropino, the central area of the ore zone has been extensively kaolinized by deep weathering to a depth of 50 m.

The recent development of alluvial and eluvial deposits in the Morrua area has led to the establishment of a processing plant that is in operation, with initial production reported to be around 45 tpa with the capacity to increase production up to about 140 tpa (Linden, 2000).

Namibia

In southern Namibia, in an area known as Tantalite Valley, there are numerous granitic rare-metal pegmatites, some as much as 12 km long by 5 km wide. In 2001 the Tantalite Valley mine, with reserves and resources estimated at 0.74 Mt at 0.0 43% Ta_2O_5, was reopened. This project, owned by Tantalum Valley Mining and expected to process 6000 tonnes/month (tpm) of tantalite ore to produce 1.5 tpm Ta_2O_5, operated for a few months only before closing due to performance problems combined with a sharp drop in the tantalite price (Mining Journal, 2002b).

In recent times in northern Namibia, there has been minor tantalite mining by local artisanal mining groups. There has also been considerable tantalite exploration in this region, particularly in the Uis area, about 290 km northwest of Windhoek. In this area, the Central African Mining and Exploration Company (CAMEC) developed a plan to redevelop old tantalite–tin deposits at the Three Aloes mine, and the B1 and C1 Pegmatites. These deposits are estimated to contain Ta_2O_5 resources of 7.2 Mt at 0.05% and 2.0 Mt at 0.024% respectively (Simmonds et al., 2002).

CAMEC recently acquired a 51% share in ABC Mines and is currently purchasing about 1.5 tpm Ta_2O_5 from the company's AB mine at Uis. CAMEC has also carried out a feasibility study on the reprocessing of tailings from the Uis slime dumps from the old ISCOR tin mine estimated to contain 4 Mt at 0.006% Ta_2O_5, 0.053% Nb_2O_5, and 0.33% tin. To set up this operation, a processing plant would have to be built at Uis to produce about 23 t of Ta_2O_5 and 65 t of tin per annum.

Also in northern Namibia, there are a number of other tantalite exploration areas around granitic rare-metal pegmatites and associated placer prospects. CAMEC is exploring in the Strathmore area, Reefton Mining have a prospect at Sandamap, and also at Nainais–Kohero in a joint venture with Rusina Mining.

Nigeria

Large tantalite deposits have been reported in Nigeria, mainly in rare-metal pegmatites and alluvial placer deposits in Nasarawa, Gombe, and the Kogi states, and in the Federal Capital Territory.

In central Nigeria, the mining of coltan has been practised for many years by artisanal mining groups. The areas around Nasarawa and the old tin mining areas of the central Jos Plateau appear to be the main focus of this industry. In these and other areas, coltan is produced by artisanal groups and is accumulated by local traders for export. For example, it is reported that artisanal workers in the Nasarawa area produce about 35 tpa of coltan, and further north at Kano about 1 t is exported by air transport each month. Linden (2000) stated that Nigerian tantalite production for 2000 was estimated to be about 90 t.

Columbia River Resources have been actively exploring old tantalite workings in areas of extensive pegmatite swarms in central Nigeria (MBendi, 2003). In 2001, the company formed an agreement with Nigeria's only official tantalum producer, Bakuwa Mining Works, to access prospecting and mining licence areas in Nasawara State. In these properties, Ta_2O_5 grades up to 0.035% have been consistently reported.

Rwanda

The coltan industry in Rwanda comprises small co-operatives and artisanal mining groups in a variety of locations, with the majority situated in an east–west zone about 30 km wide that extends through Kigali. Cunningham (2001) estimated that coltan production in 2001 was about 350 t that contained about 95 t of tantalum.

Zimbabwe

The tantalum industry in Zimbabwe also has a long history of artisanal miners who mine small quantities of tantalite and sell it to local traders who subsequently arrange for its export in bulk lots. In 2000, a rough estimate put total production at about 9.0 tpa (Linden, 2000).

Production is mainly centred around two areas. The first is Kamativi in the far west of the country, about 420 km west-southwest of Harare, and the second is in the country's northeast 100–180 km northeast of Harare in areas around Sutswe, Rusambo, and Shamva.

In March 2001, Allied Mining Investments were seeking US$7.5 million to reopen the Kamativi tin mine as a tantalum operation, after receiving Government approval to buy and operate the mine. Before closure in 1994, the mine was producing 1200 tpa of tin and about 60 tpa of tantalum concentrates (Carlin, 2001). Since its closure, approximately 82 artisanal mining groups have been known to be scavenging tin–tantalum ore from around the abandoned Kamativi mine site.

Several years ago, in the northeast of the country, CAMEC was intending to prove-up reserves in its properties and set up a 60 tonnes/hour processing plant in the Sutswe area. These properties contain the Eagle, Donsa, and Dove 14 mines, with resources of 0.61 Mt at 0.034% Ta_2O_5, 1.62 Mt at 0.025% Ta_2O_5, and 0.65 Mt at 0.044% Ta_2O_5 respectively. CAMEC also has tantalum prospects at Rusambo in the same region (Simmonds et al., 2002).

At Shamva, about 80 km northeast of Harare, the undeveloped Wanroo deposit is estimated to contain unproven reserves of 0.13 Mt at 0.07% Ta_2O_5.

Asia

Across Asia tantalum provinces, deposits, and prospects are found in eight countries in diverse locations spread throughout the continent, with the main concentration being located in the southeastern mountainous regions of the Russian Federation. Most deposit styles are represented, from the extensive terrestrial and marine alluvial placer deposits of Malaysia, Thailand, and Burma to the more unusual agpaitic nepheline syenite-hosted deposits of the Kola Peninsula in the Russian Federation. Notably, granitic rare-metal pegmatites that are so common in many other regions of the world appear to be in a minority in Asia.

Despite the presence of many reportedly large deposits, tantalum production is limited to only a few countries, mainly China, Malaysia, and Thailand, with only very small quantities currently mined in the Russian Federation. However, it should be noted that information relating to the location, geology, mineral resources, and mining activities of many of the Russian Federation tantalum mines and deposits is extremely limited.

A deposit currently attracting some attention is the Ghurayyah tantalite deposit in northwestern Saudi Arabia. Tertiary Minerals plc is carrying out a re-evaluation of this deposit and has recently identified a resource of 385 Mt at 0.025% Ta_2O_5 (Australia's Paydirt, 2002b).

A summary of the principal tantalum mines, deposits, and prospects in Asia is given in Table 23 and their locations are shown in Figures 47 and 48.

China

China has two main tantalum mining areas at Yichun in Jiangxi Province, and at Nanping in Fujian Province, together with the 801 mine in Inner Mongolia that is reportedly coming on-stream in 2003.

In addition, minor tantalum production has been reported from the Ma Ar Kan spodumene mine in Sichuan Province and the Limu tin mine in the south of the country. Tantalum produced as a byproduct in 2000 was estimated at about 11 t (Linden, 2000). Other tantalum–niobium mines are the Shicheng mine in Jiangxi Province, and the Paitan, Taimei, and Yonghan mines in Guandong; however, no details are available about these operations.

Jiangxi Province

The Yichun tantalum–niobium–lithium openpit mine, located 180 km southwest of Nanchang in Jiangxi Province, is China's biggest tantalum producer (over 54 tpa) and accounts for over half of China's output. The deposit is comparatively low grade, with proven reserves of 6800 t at 0.017 – 0.020% Ta_2O_5. The mine is also a major producer of lithium sourced from lepidolite. Further increases in production are planned, but will require significant investment on new infrastructure to succeed.

The Yichun deposit is regarded as being a model example of the rare-metal (Li–F) granite or apogranite style of deposit. In this deposit, columbite–tantalite, microlite, and Ta-rich cassiterite are present in the apogranitic body, a small sheet-like body of topaz–lepidolite granite that represents the most fractionated and latest phase of the Jurassic Yanshan batholith. This granite is composed mainly of albite, lepidolite, and quartz, with topaz, K-feldspar, amblygonite, and accessory zircon, monazite, pollucite, and the tantalum minerals mentioned above. The granite overlies an earlier sheet-like Li-mica granite (also containing minor tantalum–niobium mineralization) that in turn overlies the parent muscovite granite that occupies almost 60% of the batholith's outcrop area (Yin et al., 1995).

The mineralized topaz–lepidolite granite is characterized by the presence of a marginal 'stockscheider' that consists of a banded pegmatitic and quartz-rich porphyritic facies enriched with beryl, topaz, and tourmaline. This stockscheider separates the topaz–lepidolite granite from contact with local metasedimentary rocks at the margin of the intrusion.

A geological map and cross section of the Yanshan batholith is shown in Figure 49.

Fujian Province

The Nanping underground mine, located 130 km west-northwest of Fuzhou in Fujian Province, came into production in 2000. The operating company, Ninning Tantalum–Niobium Mining, is a joint venture partly owned by the Ningxia Non-ferrous Metals Smeltery (NNMS). It has been demonstrated that the deposit has proven reserves of 4230 t at 0.030% Ta_2O_5. The plant has been designed to produce up to 116 tpa Ta_2O_5 concentrates. Ta_2O_5 concentrates are shipped to the NNMS in Ningxia Huizu Autonomous Region for the manufacture of tantalum powder (Tse, 1997).

The Nanping tantalum deposit is situated in a large swarm of zoned granitic rare-metal pegmatites clustered around a migmatitic host granite of late Palaeozoic age. Yueqing et al. (1985) identified four distinct pegmatite zones of increasing fractionation and complexity radiating out from the host granite. The outermost zone (type IV) contained significant levels of the rare-metals elements tantalum, niobium, tin, lithium, rubidium, and caesium. Over 80 minerals, including wodginite, were identified in the type IV pegmatites.

Inner Mongolia

The 801 mine is located near Tongliao in eastern Inner Mongolia, about 640 km northeast of Beijing. The current owners are the Ningxia Non-ferrous Metals Smeltery. This mine has large resources of tantalum–niobium, rare earths, and zirconium, and the ore is accessible by open cutting. Proven reserves quoted for the deposit are 6.8 Mt and the average Ta_2O_5 grade in the upper 50 m of the deposit is 0.022%, with niobium values being considerably higher (Ningxia Non-ferrous Metals Smeltery, 2002; China Market, 2002). It was originally estimated that the mine would commence production in 2003 (Linden, 2000).

Table 23. Significant tantalum mineralization in Asia

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
China							
Jiangxi Province, 180 km southwest of Nanchang	Yichun mine	Yichun and Xin Fang mining companies	Rare-metal (Li–F) granite (apogranite)	Columbite–tantalite, microlite, Ta-rich cassiterite	Topaz, lepidolite, zinnwaldite, K-feldspar, albite, fluorite	Topaz–lepidolite granite	Proven reserves: 6 800 t at 0.017 – 0.020% Ta_2O_5
Fujian Province, 130 km west-northwest of Fuzhou	Nanping mine	Ninning Tantalum–Niobium Mining	Granitic rare-metal pegmatite	Columbite–tantalite, tapiolite, wodginite	Cassiterite, beryl, albite, pollucite, lithium, rubidium, and phosphate mineralization	Pegmatite	Proven reserves: 4 230 t at 0.030% Ta_2O_5
Inner Mongolia, Tongliao region, 640 km northeast of Beijing	801 mine	Ningxia Non-ferrous Metals Smeltery	Possibly a peralkaline granite/syenite/metasomatite	Unspecified tantalum mineralization	Beryl, zirccon, REE	Not known	Proven reserves: 6.8 Mt. Average grade in upper 50 m of deposit is 0.022% Ta_2O_5
India							
Madhya Pradesh, Surguja district, 550 km east-northeast of Bhopal	Belangi prospect	–	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Beryl, muscovite, microcline, quartz, tourmaline, garnet, magnetite, ilmenite	Pegmatite	Ta_2O_5 grades: 0.008 – 0.032%
Malaysia							
Mainly on west coast in Perak and Selangor	Onshore and offshore tin-dredging and gravel-pump mining operations	(40 tin companies operating in 2000)	Placer, mineralized deeply weathered kaolinitic regolith mainly from rare-metal (Li–F) granites	Columbite–tantalite, strüverite	Cassiterite	Granite, pegmatite, kaolin, alluvium, shallow-marine sediments	Not available
Mainly on west coast in Perak and Selangor	Retreatment of of tin tailings and tin slags	na	na	Strüverite	na	na	Not available
Mongolia							
50 km northeast of Hovd	Halzan Buregtei deposit	–	Peralkaline granite/syenite/metasomatite	Pyrochlore, columbite–tantalite	REE, zircon, yttrium oxides	Alkali microcline–albite granite	Resources: 35 000 t Ta_2O_5, 0.6 Mt Nb_2O_5, 1.0 Mt REE, 4.0 Mt ZrO_2, 0.1 Mt Y_2O_3

Table 23. (continued)

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Russian Federation							
Altai Republic, southeast Altai near Kazakhastan border	Alakhinskoye deposit	–	Rare-metal (Li–F) granite	Columbite–tantalite (secondary ore)	Spodumene, mica, feldspar	Granite	Reserves: 68 Mt at 5% Li_2O_5, 15 000–20 000 t at 0.013 – 0.017% Ta_2O_5
Chita Province, 270 km east-southeast of Chita	Etykinskoye mine	Etaginsky GOK	Rare-metal (Li–F) granite	Columbite–tantalite	Cassiterite, lithium mineralization	Granite	Proven reserves: 12 700 t at 0.013% Ta_2O_5
Transbaykalia region, southern Chita Province	Orlovskoye mine	Orlovsky GOK	Rare-metal (Li–F) granite	Columbite–tantalite	Unknown	Granite	Reserves (pre-production): 30 000 t at 0.013 – 0.015% Ta_2O_5
Chara region, northern Chita Province	Katuginskoye deposit	–	Peralkaline granite/syenite/ metasomatite	Columbite–tantalite	REE, cryolite; Zr and Y enrichment	Granite	Reserves: 774 Mt at 0.025% Ta_2O_5
Irkutsk region, eastern Sayan Mountains	Vishnyakovskoye mine	–	Granitic rare-metal pegmatite	Columbite–?tantalite	Beryl, lithium mineralization, Cs enrichment	Pegmatite	Not available
Locality not given	Beloziminskoye mine	State ownership	Mineralized deeply weathered regolith over ?carbonatite	Niobium and tantalum mineralization	Apatite	Unknown	Phosphate reserves: 20 Mt at 11.4% P_2O_5
Locality not given	Zashikhinskoye deposit	State ownership	Unknown	Niobium and tantalum mineralization	Lithium mineralization	Unknown	Not available
Murmansk region, Lovozero district, Kola Peninsula	Umbozero mine	Lovozero Mining	Agpaitic nepheline syenite	Loparite (source of Nb, Ta, Ti, and REE)	Eudialyte, microcline, apatite, sphene	Nepheline syenite	Average Ta_2O_5 grade: 0.015%
Primorskiy, 120 km north of Vladivostok	Voznesenovskoye mine	Yaroslavskiy GOK	Rare-metal (Li–F) granite	Columbite–?tantalite	Fluorite, beryl, lithium mineralization, Rb and Cs enrichment	?Granite	Resources: 17.2 Mt at 0.012% Ta_2O_5, 0.016% Nb_2O_5
Tuva Republic, locality not given	Ulug-Tanzekskoye deposit	–	Unknown	Columbite–?tantalite	–	Unknown	Resources: >5000 t at 0.01% Ta_2O_5

Table 23. (continued)

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Saudi Arabia							
85 km southwest of Tabuk	Ghurayyah deposit	Tertiary Minerals	Peralkaline granite/syenite/ metasomatite	Columbite–tantalite	Zircon; REE, U, and Th mineralization	Alkali granite plug	Resources: 385 Mt at 0.025% Ta_2O_5 , 0.284% Nb_2O_5, 0.892% ZrO_2
Thailand							
West coast peninsular Thailand (Phuket area) extending north into Burma	Numerous onshore and offshore dredging and gravel-pump mining operations	na	Placer, mineralized deeply weathered kaolinitic regolith mainly from rare-metal (Li–F) granites	Columbite–tantalite	Cassiterite, tungsten mineralization	Granite, pegmatite, kaolin, alluvium, shallow-marine sediments	Not available
	Retreatment of tin tailings and some tantalite ore	S. A. Minerals	na	Columbite–tantalite, strüverite	Cassiterite, tungsten mineralization	na	Not available
	Reprocessing of tin slags	Thiasarco	na	na	na	na	Not available
130 km south-southwest of Chiang Mai	Omkoi prospect	Unknown	Mineralized deeply weathered kaolinitic regolith over rare-metal (Li–F) granite	Columbite–?tantalite	Cassiterite, scheelite	Granite, pegmatite, kaolin	Not available

SOURCES: China — Yin et al. (1995); Yueqing et al. (1985)
India — Singh and Sharma (1997)
Malaysia — Schwartz et al. (1995)
Mongolia — Mineral Resources Authority of Mongolia (2003a)
Russian Federation — Chapleau Resources (2002a), Bisnis (2002a); Ames Laboratory (2002)
Thailand and Burma — west coast: Schwartz et al. (1995); Chiang Mai region: Metal Mining Agency of Japan (2002)
Saudi Arabia — Tertiary Minerals plc (2003)

NOTE: na not applicable

Malaysia, Thailand, and Burma

The tin industry has long been established in numerous places along the 1600 km of coastal lowlands of western Malaysia from Melaka to Georgetown, and from Phuket in Thailand northwards almost to Rangoon in Burma. In these areas, tin containing small amounts of tantalum is recovered from alluvial and eluvial terrestrial deposits, and also from offshore marine placer deposits. In 2002, it was estimated that about 24 tin mines were operating in Malaysia alone (Minerals and Geoscience Department Malaysia, 2003). Principal mining methods are by gravel pump and dredging that represents about 90% of total output.

In these areas, tin–tantalum placer deposits are derived largely from the weathering of Mesozoic biotite granites that form part of the Main Range Granitoid Province in western peninsular Malaysia and southern peninsular Thailand. Smaller quantities are derived from rare-metal pegmatites.

Figure 48. Tantalum mining provinces, mining operations, deposits, and prospects in Asia

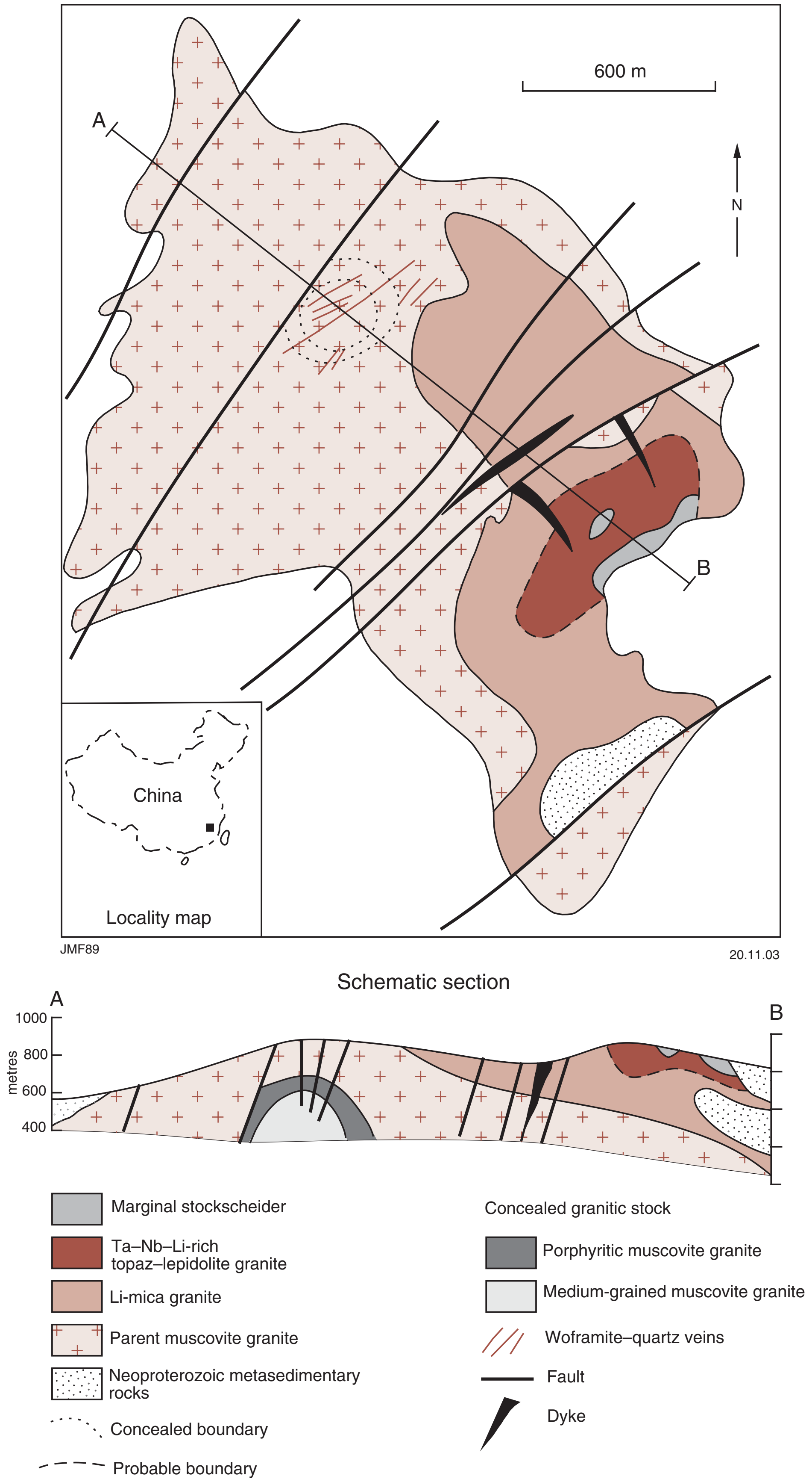

Figure 49. Geological map and schematic cross section of the Yanshan batholith. Diagram shows the relationship of the rare-metal granites overlying the parent muscovite granite. The Yichun Ta–Nb–Li deposit is located within the topaz–lepidolite granite (modified from Yin et al., 1995)

In both Malaysia and Thailand, tantalum is recovered by many small companies. The ore, mainly in the form of strüverite, is usually recovered as a byproduct of tin during secondary processing operations. Retreating of tin tailings to extract tantalum minerals is carried out in Thailand by S.A. Minerals, and in Malaysia by BEH Minerals. In 2000, these companies each recovered about 22 t of strüverite containing approximately 9–12% Ta_2O_5 (Linden, 2000).

In these countries, tantalum is also recovered from low-grade tin slags. In 2000, the Malaysian Smelting Corporation produced less than 22 t of Ta_2O_5 from this source, and in the same year the Thaisarco tin smelter in Thailand produced tin slags containing about 10% Ta_2O_5 and yielding about 45 t of tantalum pentoxide. Long-term production in this region appears to be falling due to the gradual decline in offshore tin-dredging operations.

Mongolia

Tantalum mineralization has been reported from many areas in Mongolia; however, deposits are mostly undeveloped and information is very limited. A summary of Mongolian rare-metal mineralization has been given in Kovalenko and Yarmolyuk (1995).

In central and eastern Mongolia, deposits such as Yugodzyr are incorporated in early Mesozoic rare-metal (Li–F) muscovite granites, and appear to be related to the mineralization style of the Yichun apogranite in China. However, reported grades are low at around 0.004 – 0.005% Ta_2O_5 (Kovalenko and Yarmolyuk, 1995). In the same geological environment, granitic rare-metal lithium- and/or muscovite-rich pegmatites are present and are represented by the Khukdel-Ula and Berkhin deposits. Related tantalite alluvial placer deposits are also present in some areas.

In central Mongolia, there are unusual rare-metal host rocks known as ‘ongonites’. These are topaz-bearing rhyolitic rocks enriched in lithium and fluorine, and are found as either volcanic or plutonic varieties. Plutonic ongonites often take the form of small dyke-shaped bodies up to 150–200 m long and only a few metres wide. Grades for Ta_2O_5 appear to be generally less than 0.01%, but may range up to 0.016%. Tantalum-rich ongonite deposits are present at Teg-Ula (volcanic style) and Ongon-Khairkhan (plutonic style).

The late Palaeozoic Halzan Buregtei deposit is located in northwestern Mongolia, 50 km northeast of the town of Hovd. This deposit is a peralkaline granite–metasomatite type forming part of the alkaline granites of the Halzan Buregtei Massif. Pyrochlore and columbite mineralization is concentrated in small, stock-like bodies of alkaline microcline–albite granite. Tantalum–niobium resources have been estimated at 35 000 t Ta_2O_5 and 0.6 Mt Nb_2O_5. Other significant mineralization includes zirconium oxide (4.0 Mt), rare earth oxides (1.0 Mt), and yttrium oxide (0.1 Mt). The deposit is reported to be in the exploration phase (Mineral Resources Authority of Mongolia, 2003b).

Russian Federation

Information relating to the location, geology, tantalum resources, and mining activities in the Russian Federation is extremely limited. However, it is known that there are about 20 tantalum deposits scattered across the Russian Federation. Most appear to be large, low-grade deposits that are currently uneconomic to mine because of their low-grade ore reserves, remote location, processing difficulties, lack of development capital, or a combination of these factors. Last recorded tantalum production was in 1998 from the Lovozyorskoye deposit in the Murmansk region.

Current estimates rate tantalum resources in the Russian Federation as very large; however, the average grade for Russian tantalum deposits is only 0.015% Ta_2O_5. It is believed that a large proportion of available tantalum resources is mostly contained in three large deposits: Katuginskoye in the Chita Province (774 Mt at 0.025% Ta_2O_5), Lovozyorskoye in the Murmansk region (resources not available), and Ulug-Tanzekskoye in the Tuva Republic (resources not available). Katuginskoye and Lovozyorskoye, plus the Beloziminskoye and Vishnyakovskoye deposits in the Irkutsk region (resources not available), have been identified as being generally the most economic deposits to mine and process in times of improved economic circumstances.

The most promising of the newly discovered deposits are Alakhinskoye in the Altai Republic with 15 000–20 000 t at 0.013 – 0.017% Ta_2O_5 (Chapleau Resources, 2002b), Voznesenovskoye and Progranichnoye in the Primorskiy region near Vladivostok with 17.2 Mt estimated at 0.012% Ta_2O_5 and 0.016% Nb_2O_5 (Bisnis, 2002b), and Zashikhinskoye in the Irkutsk region (resources not available).

Data relating to the tantalum deposits in the Russian Federation are shown in Table 23.

Saudi Arabia

The Ghurayyah tantalite deposit located in northwestern Saudi Arabia, about 85 km southwest of Tabuk, is currently being re-evaluated by Tertiary Minerals. The company has recently identified a tantalum resource of 385 Mt at 0.025% Ta_2O_5 to a depth of 250 m (Australia’s Paydirt, 2002b).

Ghurayyah is a peralkaline granite–syenite–metasomatite deposit hosted within a 900 m-diameter plug of alkali granite. The plug protrudes approximately 60 m above ground level. This section of the deposit contains about 10 Mt of the estimated resource, thus making for comparatively easy initial mining. Other identified resources included in the 385 Mt of ore are 0.284% Nb_2O_5 and 0.892% ZrO_2 (Tertiary Minerals plc, 2003).

South America

Four countries in South America have recorded tantalum deposits. Apart from Brazil, the world’s second-largest tantalum producer, Bolivia and Guyana produce limited quantities of tantalum mined by small companies, local cooperatives, and artisanal miners from small workings and alluvial deposits. In recent years, tantalum exploration programs have been conducted in these two countries.

In French Guiana, small quantities of alluvial tantalite ore have been mined from about 12 sites (Gurmendi, 1997). Between 1969 and 1991 about 80–90 t of columbite–tantalite ore was produced. No other information about these operations is available.

A summary of the principal tantalum mines, deposits, and prospects in South America is given in Table 24 and their locations are shown on Figure 50.

Bolivia

The Santa Cruz Province in eastern Bolivia extends over large areas of the Precambrian Bolivian Craton that contains extensive granite–greenstone areas. In 2001, the General Minerals Corporation – Ranger Minerals joint venture explored three tantalum prospects about 160 km east of the city of Santa Cruz. The prospects of Agua Dulce, Rio Blanco, and Los Patos are zoned rare-metal pegmatites with associated colluvial and alluvial placers containing anomalous levels of tantalum and niobium. In its program of exploration, the joint venture carried out costeaning of weathered pegmatite and adjacent colluvial material. Geochemical values for Ta_2O_5 ranged from 0.003 to 0.020%. In October 2001, the joint venture was conducting bulk-washing trials from colluvial material to evaluate tantalite concentrate potential. Possible commercial quantities of muscovite mica occur at Agua Dulce and Los Patos, as well as alkali feldspar at Agua Dulce (General Minerals Corporation, 2002).

Brazil

Brazil is the world's second-largest tantalum producer after Australia, with production in 2001 estimated at 300 t, and an estimated reserve base of 53 000 t (Cunningham, 2002). Tantalum mineralization has been reported from Amazonas, Minas Gerais, Rondônia, and Bahia states, and most deposits appear to be related to or derived from Archaean–Palaeoproterozoic albitic granites or rare-metal pegmatites.

Artisanal mining

Artisanal mining is common in many areas of Brazil. This is carried out as small alluvial mining operations, mainly by local prospectors known as 'garimperos'. Apart from much artisanal mining in the Pitinga area in Amazonas State, the garimperos are active in tin–tantalum areas in Minas Gerais and Bahia states. Another area of interest is in the tin mining district of Bom Futuro, about 210 km east-southeast of Porto Velho in Rodônia State in the far west of Brazil. Here, there are many alluvial operations extracting tin and tantalite derived from Archaean–Palaeoproterozoic peraluminous, greisenized, albitic granite. Linden (2000) estimated that the Brazilian garimperos mine and sell about 45 tpa of tantalite each year.

Amazonas

The country's largest mine is at Pitinga, located in northern Brazil in Amazonas State, about 260 km north of Manaus. In this area of the Archaean–Palaeoproterozoic Amazon Craton, there are extensive areas of cassiterite and columbite–tantalite mineralization associated with granites or eluvial and alluvial placer deposits. The Pitinga mine, owned by Paranapanema SA, is a 12 000 tpa tin mine producing tantalum and niobium concentrates as by-products. Current operations are largely dredge mining of cassiterite and columbite–tantalite alluvial placer deposits to a depth of 8 m. It appears that available resources in these deposits are becoming limited and a change will eventually have to be made to mining tin–tantalum–niobium resources from existing deposits in peralkaline albite granites. It is known that the company has plans to develop the hard-rock mine to ultimately produce about 450 tpa Ta_2O_5.

At the mine site, tin and columbite–tantalite primary concentrates are produced. The columbite–tantalite concentrate is transported to the Sao Tiago oxide plant near Sao Paulo in eastern Brazil, where approximately 100 tpa of refined Ta_2O_5 is produced. The company's nearby Mamore tin smelter has large stockpiles of tin–tantalum–niobium slags that are estimated to contain almost 2270 t of Ta_2O_5; however, extraction of refined Ta_2O_5 from this resource is likely to prove difficult (Linden, 2000).

Paranapanema SA has a subsidiary company Taboca that operates a tantalum mine further south in Amazonas, near Manaus; however, no details of this operation are available.

Minas Gerais

The Nazareno mine is located 40 km west-southwest of Sao Joao del Rei in Minas Gerais State. The tantalite deposit is likely to be related to granitic rare-metal pegmatites emanating from a peraluminous granite forming part of the Archaean–Palaeoproterozoic Sao Francisco Craton of eastern Brazil. The mine, operated by Cia. Industrial Fluminense (a wholly owned subsidiary of Metallurg Inc.), is designed to produce up to 45 tpa Ta_2O_5. The company operates a tantalum and niobium extraction plant near Sao Joao del Rei in conjunction with a small tin smelter that also produces a tantalum-rich slag. The company also buys tin and tantalite from other local producers for processing with the Nazareno concentrates. Together with Ta_2O_5 refined from slag, total refined Ta_2O_5 production is about 127 tpa (Linden, 2000).

Guyana

Current tantalum prospecting in Guyana is concentrated in the Morabisi area, about 190 km west-southwest of Georgetown. At this locality, an oval-shaped

Table 24. Significant tantalum mineralization in South America

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Bolivia							
Santa Cruz Province, Precambrian shield area, eastern Bolivia	Small deposits and workings	Small mining companies and cooperatives	Placer, granitic rare-metal pegmatites	Columbite–tantalite	–	Stream sediments, pegmatite	Not available
160 km east of Santa Cruz	Agua Dulce prospect Rio Blanco prospect Los Patos prospect	General Minerals Corporation/ Ranger Minerals	Placer, granitic rare-metal pegmatites	Columbite–tantalite	Muscovite, K-feldspar, kaolin, rutile, ilmenite	Stream sediments, pegmatite	Ta_2O_5 grade: (Agua Dulce) 0.003 – 0.020% (geochemical samples)
Brazil							
Amazonas, Minas Gerais, Rondônia, Bahia states	Numerous small alluvial deposits	Small mining operations and artisanal miners	Placer	Columbite–tantalite	Cassiterite	Stream sediments	Not available
Amazonas State, 260 km north of Manaus	Pitinga dredging operation	Paranapanema SA	Placer, peralkaline granite/syenite/ metasomatite	Columbite–tantalite	Cassiterite, zircon, REE, cryolite	Stream sediments, granite	Substantial resources
Minas Gerais State, 40 km west-southwest of Sao Joao del Rei	Nazareno mine	Cia. Industrial Fluminense (Metallurg Group)	Granitic rare-metal pegmatite	Columbite–tantalite, microlite	Cassiterite	Pegmatite	Not available
Guyana							
190 km west-southwest of Georgetown	Morabisi prospect	Artisinal mining	Placer, granitic rare-metal pegmatite	Columbite–tantalite	REE, base metals; Mn, U, and W mineralization	Stream sediments, pegmatite	Anomalous Ta geochemical values: 200–2700 ppm
190 km west-southwest of Georgetown 190 km west-southwest of Georgetown	Morabisi mine Kunaballi mine	Tanimex	Placer	Columbite–tantalite, euxenite	Ilmenorutile, ilmenite, xenotime, rutile, beryl	Stream sediments	Resources: 1.53 Mm^3 of alluvial material containing about 0.89 – 1.48 kg/m^3 of Ta minerals

SOURCES: Brazil — Metallurg (2002); Paranapanema SA (2002); National Department of Mineral Production Brazil (2002)
Guyana — Guyana Geology and Mines Commission (2002)
South America (general) — U.S. Geological Survey (2002)

Figure 50. Tantalum mining operations, deposits, and prospects in South America

Mesoproterozoic granitic mass is present. The granite body is about 10 km wide and is ringed by dolerite dykes and gabbroic sills. The granite hosts a number of rare-metal pegmatites containing concentrations of columbite–tantalite and associated rare earth elements, manganese, tungsten, and uranium. Structural concordance of the pegmatites with margins of the surrounding mafic intrusions indicates that the pegmatites may have been formed by the intrusion of a subsurface mafic body causing partial melting of the granite. A geochemical survey carried out in the area detected stream-sediment values for tantalum in the range 200–2700 ppm (Guyana Geology and Mines Commission, 2002).

Alluvial and eluvial tantalite-rich placer deposits have been identified in surrounding areas. Investigations by Tanimex Inc. in the Morabisi and nearby Kunaballi areas have identified approximately 1.53 Mm^3 of workable alluvial placer deposits extending over large areas, and estimated to contain about 0.9 – 1.5 kg/m^3 of tantalum minerals (Geolisting.com, 2003).

Europe

Currently there is no tantalum production in Europe. Portugal and France are countries with a previous history of tantalum mining. In recent years, tantalum exploration programs have been carried out in Finland, Ireland, and Spain.

A summary of the principal tantalum mines, deposits, and prospects in Europe is given in Table 25 and their locations are shown on Figure 51.

Finland

In August 2000, Tertiary Minerals began an exploration program for tantalum at Rosendal, located on Kemio Island in southwest Finland. The Rosendal deposit is a rare-metal pegmatite dyke that had been previously discovered and evaluated by the Geological Survey of Finland. At that time, resources were estimated at 1.3 Mt at 0.029% Ta_2O_5 and 70% Na-feldspar to 100 m depth (Minesite.com, 2002).

Tertiary Minerals completed a 14-hole drilling program in May 2002 to evaluate the geometry of the pegmatite dyke and to carry out a revised resource estimate. Drillhole results ranged from 0.024% Ta_2O_5 over 20.2 m to 0.128% Ta_2O_5 over 3.0 m, and the weighted average Ta_2O_5 grade from the drilling program was 0.035%. The exploration program also showed the dyke to be at least 500 m in length and open at depth (Mining Journal, 2002c).

Tertiary Minerals is looking at the possibility of developing a multi-purpose mine by also processing Na-feldspar that could be recovered from the gravity tailings once the rare-metals have been removed. The company's study has revealed that from a 150 000 tpa openpit mining operation it may be possible to produce almost 30 tpa Ta_2O_5 concentrates and about 84 000 tpa premium-grade sodium feldspar (Industrial Minerals, 2002b).

France

The Beauvoir–Echassières mine in the Massif Central region of central France is located in a small leucogranite stock within the late Palaeozoic Echassières massif. Mineralization is contained within the late-phase rare-metal Beauvoir Granite that takes the form of a mineralized cupola overlying the host granite and is of a style similar to the Yichun apogranite deposit in China. The deposit contains estimated resources of 20 000 t at an average 0.012% Ta_2O_5, as well as significant grades of tin, lithium, and niobium. The deposit is also deeply weathered in places, which has permitted the mining of high-grade kaolin for use as china clay (Raimbault et al. 1995).

Currently, rare-metal mining from the deposit is inoperative, partly due to metallurgical problems associated with lithium recovery and also due to environmental concerns.

Ireland

In the Blackstairs Mountains near Carlow in the southeast of the Republic of Ireland, late Ordovician granites intrude

Table 25. Significant tantalum mineralization in Europe

Country/province/site	*Mine/deposit/prospect*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Finland							
Kemio Island, 50 km south-southeast of Turku	Rosendal deposit	Tertiary Minerals	Granitic rare-metal pegmatite	?Columbite–tantalite	Na-feldspar, quartz, mica	Pegmatite	Resources (1989): 1.3 Mt at 0.029% Ta_2O_5. Drilling (2002): 0.024% Ta_2O_5 over 20.2 m to 0.128% Ta_2O_5 over 3 m
France							
Allier, Massif Central region	Beauvoir–Echassières mine	Société des Kaolins de Beauvoir	Mineralized, deeply weathered regolith over rare-metal (Li–F) granite	Columbite–tantalite, microlite	Lepidolite, topaz, albite, cassiterite, fluorite, kaolin, zinnwaldite, phosphate mineralization	Kaolinized granite	Resources: 20 000 t at 0.012% Ta_2O_5 (average grade) (maximum grade = 0.03%)
Ireland							
Carlow, about 25 km south-southeast of Carlow	Blackstairs Mountains prospect	Angus & Ross	Rare-metal (Li–F) granite	Columbite–?tantalite	Lithium and tin mineralization	Granite, pegmatite	Peak Ta values: 0.001 – 0.002% (soil samples)
Portugal							
Guarda, 18 km south-southwest of Pinhel	Gonçalo prospect	–	Granitic rare-metal pegmatite	Columbite–tantalite (secondary ore)	Lepidolite, cassiterite, beryl	Pegmatite	Not available
Viana do Castelo, 10 km northeast of Caminha	Serra de Arga area prospects		Rare-metal (Li–F) granite	Columbite–?tantalite	Cassiterite	Granite	Not available
Spain							
Pontevedra, Forcarey area, 50 km northeast of Vigo	Forcarey Sur prospect	Golden Dynasty Resources	Granitic rare-metal pegmatite, rare-metal (Li–F) granite	Columbite–tantalite, strüverite	Cassiterite, spodumene, beryl, albite, phosphate mineralization	Pegmatite, kaolinized and greisenized granite	Inferred resources: 7.35 Mt Indicated average grade: 0.016% Ta_2O_5, 0.109% Sn

SOURCES: Finland — Minesite.com (2002)
France — Raimbault et al. (1995)
Ireland — Angus & Ross plc (2000)
Portugal and Spain — U.S. Geological Survey (2002)

Figure 51. Tantalum mining operations, deposits, and prospects in Europe

a sequence of early Palaeozoic metamorphosed sedimentary and volcanic rocks. In the area of the granite–sedimentary rock interface is a major deformation zone trending northeast. Pegmatite and microgranite intrusions are distributed along 35 km of this zone.

In 2001, Angus & Ross carried out soil and stream-sediment sample geochemical surveys in the area. Exploration was based on anomalous values for tantalum from a previous stream-sediment survey conducted by the Geological Survey of Ireland. Results from the earlier survey indicated that anomalous tantalum values were only partially coincident with the zone of pegmatite intrusion.

In the soil geochemical survey subsequently carried out by Angus & Ross, 1895 samples were collected over an area of about 15 km^2. Peak values for the soil geochemical survey were 10–20 ppm Ta (Angus & Ross plc, 2000). Distribution of tantalum anomalies from this survey indicated that the tantalum mineralization may be related to a rare-metal (Li–F) apogranite. Follow-up trenching and drilling surveys are planned.

Portugal

In Portugal, minor tantalum mineralization is associated with a long-established tin-mining industry at Serra de Arga in the northwest of the country, where tin has been mined from post-tectonic rare-metal granites. Tantalum is also associated with lithium contained in aplitic pegmatites embedded in late Palaeozoic granites in the Gonçalo area in eastern Portugal.

Spain

The Forcarey Sur tantalum prospect is located about 50 km northeast of Vigo in northwest Spain. In this area, late Palaeozoic micaceous, peraluminous granites were intruded into Silurian to Devonian sedimentary rocks, resulting in localized metamorphism to greenschist–amphibolite facies. Late-phase, zoned rare-metal pegmatites were subsequently intruded into the resulting schistose metasedimentary rocks. Albite-rich zones within the pegmatites have been enriched in beryllium, lithium, tantalum, niobium, tin, and phosphorus.

In 1999, Golden Dynasty Resources identified two pegmatite zones along a strike length of 2 km and with average widths of 10 m (Newman, 1999). Previous investigations indicated that these areas may contain inferred resources of 7.35 Mt at indicated average grades of 0.016% Ta_2O_5 and 0.109% Sn. A spodumene resource was also identified within these zones, but no analytical values for lithium were reported.

Additional reconnaissance in the area identified numerous zones of tantalum mineralization present in other pegmatites and greisenized, kaolinized granites.

Chapter 11

Tantalum resources of eastern Australia

New South Wales

In New South Wales there are only two sites of recent activity for tantalum exploration. The first of these is at Jingellic on the Murray River in the southeast of the State. This project is an extension of Tantalum Australia's Walwa tantalum project located across the river in Victoria. The New South Wales portion of this project is presently under application for an exploration licence.

The second project is the Toongi zirconium project operated by Australian Zirconia. This project, located near Dubbo in central New South Wales, is principally directed toward zirconium mining and processing. However, the deposit also contains substantial tantalum–niobium resources that are intended for recovery as byproducts during the zirconium concentrate process.

A summary of the tantalum projects in New South Wales is given in Table 26 and their locations are shown on Figure 52.

Jingellic

Tantalum Australia has applied for an exploration licence in the Jingellic area on the Murray River, in the southeast of the State. The application area extends about 12 km north of Jingellic and 23 km east–west of the town. The area is located in and around the Silurian Corryong Granite and surrounding metasedimentary rocks. Some interest has been shown in old tin mining areas at Swamp Creek and Jingellic. Regional reconnaissance by the company during 2002 in this area, and across the Murray River at Walwa in Victoria, yielded rock-chip samples with Ta_2O_5 values up to 0.037% (Tantalum Australia NL, 2002b).

Toongi

The mineralized Toongi intrusion is located 22 km south of Dubbo in central New South Wales. The intrusion is an altered trachytic plug forming part of a local suite of Jurassic alkaline intrusive and extrusive bodies. The original trachyte has undergone significant carbonate, chloritic, potassic, and argillic alteration, and is also deeply weathered. The plug appears to be a near-vertical body of mostly uniform altered trachyte, with dimensions of 900 m in an east–west direction and 500 m in a north–south direction. The central core of the intrusion contains a small area of coarsely crystalline unaltered trachyte that is subject to major ore-grade variations.

Since early 2001, the Toongi plug has been the subject of extensive exploration and metallurgical testing by Australian Zirconia, a wholly owned subsidiary of Alkane Exploration. Recently, a detailed drilling program over the orebody yielded total measured and inferred resource of 83 Mt at 1.91% ZrO_2, 0.027% Ta_2O_5, 0.448% Nb_2O_5, O.720% REE, 0.041% HfO_2, and 0.138% Y_2O_3 (Alkane Exploration Ltd, 2002).

Mineralization in the deposit is very fine grained and the only ore minerals identified to date are zircon and niobium-rich aeschynite (a niobium–tantalum–titanium mineral that may also contain the rare earths yttrium and caesium).

In May 2002, following encouraging zircon and niobium–tantalum recovery results from mini-pilot plant trials, the company announced that it would proceed with the construction of a 1:500-scale pilot plant designed to process 10 t of ore and produce 100 kg of zirconium and niobium–tantalum concentrates. Assuming a successful outcome of these trials, the company anticipates a move to commercial production based on a processing capacity of 200 000 tpa. Estimated annual production would be 3500 t of zirconia, 900 t of tantalum–niobium concentrate, and 1000 t of yttrium-rich rare earths (Industrial Minerals 2002c).

In October 2003, the company reached agreement with Astron Ltd to facilitate project development, including funding for the pilot plant. This plant is due to be in production within twelve months of the agreement date (Minmet Ozmine, 2003).

Northern Territory

There are numerous recorded localities of tantalum mineralization in the Northern Territory. Only areas of significant tantalum mineralization that have attracted recent exploration programs are discussed in this chapter. A comprehensive account of all tantalum deposits in the territory is contained in Eupene Exploration Enterprises (1989).

A summary of the principal tantalum deposits, prospects, and exploration area in the Northern Territory is given in Table 27 and their locations are shown on Figure 52.

Table 26. Significant tantalum mineralization in New South Wales

Mine/deposit/prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Jingellic prospect	70 km east-northeast of Albury	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Not available
Toongi deposit	22 km south of Dubbo	Australian Zirconia	Peralkaline granite/syenite	Tantalum–niobium mineralization including Nb-rich aeschynite	Zircon, Y–REE mineralization	Altered trachyte plug	Measured and inferred resources: 83.0 Mt at 1.91% ZrO_2, 0.448% Nb_2O_5, 0.027% Ta_2O_5, 0.138% Y_2O_3, 0.720% REE

SOURCES: Jingellic — Tantalum Australia NL (2002b)
Toongi — Alkane Exploration Ltd (2002)

Barrow Creek

An area of tin–tantalum–tungsten mineralization is located in an arc approximately 15–30 km to the northwest and north of the township of Barrow Creek. This area covers numerous prospecting pits that have spasmodically produced limited quantities of these metals from the early 1900s to the 1950s. Mineralization is hosted by steeply dipping pegmatite dykes and quartz veins, trending in a northerly direction, that have intruded quartz–mica schist and amphibolite of probable Palaeoproterozoic age. The pegmatites and quartz veins are probably late-phase intrusions emanating from the nearby Proterozoic Barrow Creek Granite. The host rocks are strongly sheared and faulted, and a number of pegmatite dykes are present in shear zones close to the parent granite.

In this area, tantalum has been recovered from the Millers, Tommys, and Richards mines, and the Johannsens, Slippery, Ringing Rocks, and Anster prospects. Freeman (1978) reported that Millers mine, about 17 km north-northeast of Barrow Creek, consisted of a quartz reef and surrounding eluvial material containing tantalum mineralization. About 150 kg of tantalite ore was extracted from a 2.0 m-deep pit over the quartz reef in previous mining operations.

More recently, attention has been focused on local regolith material that may be prospective for eluvial and alluvial placer deposits. Geochemical sampling about 3 km southwest of Millers mine has yielded sporadic tantalum values up to 1288 ppm (Forthsythe, 1981). In 2001 Glengarry Resources (Glengarry Resources Limited, 2001a), and Goldstake Explorations (Goldstake Explorations Inc., 2001) carried out appraisals of the tantalum potential over adjacent areas of the Barrow Creek tantalum–tin field; however, no additional information is available.

Bynoe – Mount Finniss

The Bynoe – Mount Finniss tin–tantalum exploration province is a 15 km-wide zone extending from Bynoe Harbour (15 km south-southeast of Darwin) southwards for about 65 km. This area contains numerous tin–tantalum–niobium granitic rare-metal pegmatites and greisens that have intruded Palaeoproterozoic metasedimentary rocks (mainly metagreywacke, slate, and metashale).

The pegmatites vary in length from 2 to 200 m, and from less than 1 to 80 m in width. They trend in a northerly direction, parallel to the dominant direction of shearing and the regional trend of fold axes in the host metasedimentary rocks. The majority of the pegmatites are zoned and lenticular in shape, and in most of them the feldspars have been kaolinized by deep weathering processes. On lower hillslopes adjacent to some pegmatites, small-scale, eluvial tin–tantalum deposits have formed.

In this region, mining has been in progress since the discovery of tin in the local area in 1886, and there are records of 34 mines and 46 prospects up until 1957

Figure 52. Tantalum deposits, prospects, and exploration province in eastern Australia

(Summers, 1957) and over 100 known mineral occurrences, with at least 72 being tantalite-bearing pegmatites. Production of tin and tantalum has mainly been from mineralized pegmatite lodes, with minor production from eluvial and alluvial placer deposits. Between 1886 and 1956, an estimated 586 t of tin and 15 t of tantalum concentrates were produced. This was followed up with additional production between 1957 and 1985 of an estimated 1105 t of tantalum concentrates (Eupene Exploration Enterprises,1989).

In 1999, Sons of Gwalia was mining tantalite ore under a tribute agreement with local prospectors in the northern part of the area adjacent to Bynoe Harbour. The agreement provided for the production of 136 tpa of tantalite ore to be supplied to the company's Greenbushes plant in Western Australia for the production of high-grade tantalum concentrate (Sons of Gwalia Ltd, 1999). In 2000–01 the company also carried out tantalum exploration in the northern Bynoe area, with limited success.

Between June and the end of October 2001, Julia Corporation carried out an intensive tantalum exploration program over a large part of the Bynoe – Mount Finniss exploration province (Minmet Ozmine, 2002b). The first area drilled was the Labelle tantalum–tin deposit, with a previously reported indicated resource of 0.14 Mt at 0.013% Ta_2O_5 and 0.016% SnO_2. Twenty-two holes were drilled that yielded peak drillhole values of 0.223% Ta_2O_5 over 9.0 m. Eight costeans were then excavated over the deposit, from which a peak value of 0.153% Ta_2O_5 was obtained.

Attention then turned to the Angers prospect where ten drillholes were sunk, yielding a peak grade of 0.73% Ta_2O_5 over 3.0 m. The Beatas prospect located nearby was then drilled with four drillholes yielding high grades of 0.172% Ta_2O_5 over 3.0 m.

About the same time, Julia Corporation's exploration program at the Leviathan prospect identified 27 pegmatite bodies up to 200 m in length and 30 m width. Peak grades of 0.086% Ta_2O_5 were reported from 19 costeans.

Other prospects set down for evaluation by Julia Corporation included Northern Reward, Centurion, Twin Hills, Jim Jim, Trojan, and Burnetts. However, no further details are available following the sudden termination of the project near the end of 2001.

Mount Shoobridge

In the Mount Shoobridge area, about 125 km south-southeast of Darwin, regionally metamorphosed

Table 27. Significant tantalum mineralization in the Northern Territory

Mine/deposit/prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Angers prospect	Bynoe – Mount Finniss area, 60–90 km south-southwest of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Peak grade: 0.73% Ta_2O_5 over 3.0 m (drill sample)
Barretts – Mount Shoobridge prospect	Mount Shoobridge area, 125 km south-southeast of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Colombite–tantalite	Cassiterite	Pegmatite	Peak grade: 0.027% Ta_2O_5 over 11 m (drill sample)
Barrow Creek **p**rospects	250 km north of Alice Springs	Glengarry Resources	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, stream sediments	Not available
	260 km north of Alice Springs	Goldstake Explorations	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, stream sediments	Not available
Beatas prospect	Bynoe – Mount Finniss area, 60–90 km south-southwest of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Peak grade: 0.172% Ta_2O_5 over 3.0 m (drill sample)
Bynoe prospect	Bynoe – Mount Finniss area, 40 km south of Darwin	Sons of Gwalia/ prospectors	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, stream sediments	Not available
Labelle deposit	Bynoe – Mount Finniss area, 78 km south-southwest of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Indicated resource: 140 000 t at 0.013% Ta_2O_5 and 0.016% SnO_2. Drill sample: O.223% Ta_2O_5 over 9.0 m
Leviathan prospect	Bynoe – Mount Finniss area, 60–90 km south-southwest of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Peak grades: 0.086% Ta_2O_5 and 0.060% SnO_2 (drill samples)
Mount Finniss deposit	Bynoe – Mount Finniss area, 55 km south-southeast of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Estimated resources (1989): 0.72 Mt Sn and Ta ore and tailings
Mount Shoobridge prospect	125 km south-southeast of Darwin	Julia Corporation	Placer, granitic rare-metal pegmatite	Colombite–tantalite	Cassiterite	Stream sediments, pegmatite	Stream sediment sample: 0.7% Ta_2O_5, 1.4% Nb_2O_5, 0.2% SnO_2

Table 27. (continued)

Mine/deposit/prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Northern Reward – Centurion prospects	Bynoe – Mount Finniss area, 60–90 km south-southwest of Darwin	Julia Corporation	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite	Pegmatite	Not available
Two Bobs prospect	Mount Shoobridge area, 125 km south-southeast of Darwin	Julia Corporation	Placer, granitic rare-metal pegmatite	Colombite–tantalite	Cassiterite	Stream sediments, pegmatite	Panned concentrate: 2.9% Ta, 3.72% Nb, 0.23% Sn
Utopia prospect	175 km north-northeast of Alice Springs	Goldstake Explorations	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Bismuthinite, cassiterite, tourmaline, beryl	Pegmatite	Not available

SOURCES: Eupene Exploration Enterprises (1989); Minmet Ozmine (2002a); Bynoe and Mount Shoobridge — Minmet Ozmine (2002b,c)

Palaeoproterozic sedimentary rocks have been intruded by pegmatites and quartz veins from the nearby Mesoproterozoic Shoobridge Granite, via the Mount Shoobridge Fault and associated shear zones.

Mount Shoobridge is an old tin-mining area where mining operations have been carried out intermittently from 1882 to about 1983. The Mount Shoobridge mine was the largest operation, with four shafts up to 55 m deep and 120 m of drives on three levels. Workings were on a narrow, steeply dipping quartz–muscovite reef trending northwest, and also from pegmatite and greisen stringers. Total recorded production is 145 t of tin concentrate (Crohn, 1968).

About 2.5 km to the south is Barretts mine, situated on an irregular body of griesen and pegmatite that also trends to the northwest. This body is 91 m long, 27 m wide, and dips 30° to the northeast. The mine comprised shallow shafts, costeans, and openpits, and produced 115 t of tin concentrate during its working life.

In 2001, Julia Corporation carried out exploration in the area covering the deposits at Mount Shoobridge and Barretts, and also the large Two Bobs pegmatite prospect. Stream-sediment samples from a pegmatite at Mount Shoobridge yielded 0.7% Ta_2O_5, 1.4% Nb_2O_5, and 0.2% SnO_2. This was followed up by a drilling program in the Mount Shoobridge – Barretts area that yielded a peak value of 11 m at 0.027% Ta_2O_5 over 20 m (Minmet Ozmine, 2002c).

Field mapping of the Two Bobs pegmatite by the company showed it to be a series of parallel and interconnecting pegmatite bodies with a strike length greater than 3 km and an estimated average width of 100 m (maximum 300 m), making it the largest known pegmatite in the local area. Stream-sediment sampling in the vicinity of the Two Bobs pegmatite yielded panned-concentrate peak values of 2.9% Ta, 3.72% Nb, and 0.23% Sn (Julia Corporation Limited, 2001).

Utopia

The Utopia tantalite prospect, located 175 km north-northeast of Alice Springs and 10 km west of Utopia Homestead, is a narrow northwest-trending granitic rare-metal pegmatite dyke about 50 m in length. Host rocks are gneiss and minor schist located within 2 km of a Palaeoproterozoic granite body. Other pegmatite ore minerals include bismuthinite, cassiterite, and beryl.

Between 1949 and 1981, 1.4 t of tantalite was extracted from costeans and pits in eluvial material adjacent to the pegmatite. Exploration in the early 1980s discovered low-grade tantalum contained in eluvial and alluvial zones in the area of the pegmatite (Eupene Exploration Enterprises, 1989).

In 2001, Goldstake Explorations applied for an exploration licence over the area covering the mine site in order to further evaluate the tantalum potential of the area.

Queensland

Tantalum exploration in Queensland to date has been limited to four areas, two of which, namely Georgetown and Mount Carbine in the north of the State, are old gold and tin–tungsten mining areas respectively. The other two localities are at Homestead, southwest of Townsville, and Sybella, south of Mount Isa.

A summary of the principal tantalum prospects in Queensland is given in Table 28 and their locations are shown on Figure 52.

Georgetown

In 2001, two companies applied for exploration licences to explore for tantalite in the Georgetown area of central-northern Queensland. The first of these, Kagara Zinc, applied for an area 16 km south of Georgetown in the area of an old tantalum mine on the Delaney River, the site of previous alluvial tantalite-mining operations (Minmet Ozmine, 2001).

The other exploration area at Mistake Creek, 20 km north of Georgetown, has been taken out by Tantalum Australia. Stream-sediment samples in this area contain anomalous tantalum values (Tantalum Australia NL, 2002b).

Tantalum-bearing stream sediments in both areas appear to have been derived from local granitic rare-metal pegmatites, probably derived from the Neoproterozoic Forsayth Granite that is present throughout the area.

Homestead

In 1984, Freeport of Australia carried out a heavy metal stream-sediment survey in the Homestead area, about 170 km southwest of Townsville and 10 km north of the Thalanga base-metal mine. The survey returned values of 0.24% Ta, 0.73% Nb, and greater than 1.0% rare earths. This is an area consisting of Middle Palaeozoic muscovite granite and adamellite that has been subject to late-phase intrusion by sheets of garnetiferous muscovite pegmatite, aplite, and other granite.

In late 2000, Glengarry Resources applied for an exploration licence to carry out follow-up exploration over this area considered prospective for tantalite and rare earths mineralization. To date, limited rock-chip sampling of altered albitized pegmatites in the area has yielded values of up to 0.003% Ta (Glengarry Resources Limited, 2001b).

Mount Carbine

Rusina Mining took out an exploration licence in 2001 in the Mount Carbine area, about 75 km northwest of Cairns in north coastal Queensland. While the exploration was primarily focused on the search for tungsten, it was found that the area also hosted numerous hard-rock tin–tantalum prospects. Potential alluvial tin–tantalum placer prospects were also of interest.

At Mount Carbine, both in and around the Palaeozoic Mareeba Granite, are small areas of greisen and tourmaline-bearing granite, as well as pegmatite and aplite veins and granitic dykes. These bodies are thought to be the source of local alluvial cassiterite (and minor tantalite) worked in earlier mining operations (Amos and de Keyser, 1964).

Sybella

In early 2001, Glengarry Resources carried out a preliminary assessment for tantalite deposits on an exploration licence area at Sybella, about 10 km south of Mount Isa. Numerous beryl and some tantalite occurrences in this area are associated with pegmatites, especially those located in regional shear zones close to the Palaeoproterozoic zoned and fractionated Sybella Granite. At nearby Mica Creek, small quantities of mica, tantalum, and tin were recovered in earlier mining operations. The area is also prospective for large-scale eluvial-tantalite enrichment in deeply weathered regolith zones adjacent to local pegmatites (Glengarry Resources Limited, 2001c).

Victoria

The only area prospective for tantalum in Victoria is in the Walwa district, about 80 km east-northeast of Wodonga in the northeast of the State. In this area, tantalum exploration has been centred around old tin fields at Mount Alwa, Mount Alfred, and Burrowye, as well as a number of local prospects.

A summary of the principal tantalum deposits and prospects in Victoria is given in Table 29 and their locations are shown on Figure 52.

Walwa

The Walwa tin field was the principal producer of tin from hard-rock mining in the area. Tin mining commenced in 1882 and continued sporadically until 1968. Between 1911 and 1968 the Walwa tin field produced 166.9 t of tin concentrate (Simpson et al., 2001). Mines included Mount Alwa, Alwa South, The Bounce, and Redbank. Minor tin placer deposits were also found in colluvial material near the Mount Alwa mine.

The Walwa tin field is located in a roof pendant of Ordovician metasedimentary rocks consisting of schist and hornfels. These rocks have been intruded by cassiterite-rich leucogranite and pegmatite dykes and pods, and quartz veins derived from the underlying Silurian Corryong Granite. Mineralized dykes are variably albitized and greisenized, and may either take the form of short, narrow, steeply dipping bodies trending north-northwest, or may be comparatively large subhorizontal, irregular pods.

In 2001, Tantalum Australia acquired exploration licences in the Walwa – Mount Alfred and Burrowye areas to explore for commercial-grade tantalum mineralization.

Table 28. Significant tantalum mineralization in Queensland

Mine/deposit/prospect	*Location/site*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/grades*
Georgetown prospects	16 km south of Georgetown	Kagara Zinc	Placer	Columbite–tantalite	–	Stream sediments	Not available
	Mistake Creek, 20 km north of Georgetown	Tantalum Australia	Placer	Columbite–tantalite	–	Stream sediments	Not available
Homestead prospect	170 km southwest of Townsville	Glengarry Resources	?Peralkaline granite/syenite, placer	Columbite–tantalite	REE	Alkali granite, pegmatite, and aplite	Ta: 0.24%, Nb: 0.73%, REE: >1.0% (geochemical stream-sediment values)
Mount Carbine prospect	75 km northwest of Cairns	Rusina Mining	Placer, granitic rare-metal pegmatite	?Columbite–tantalite	Wolframite, scheelite, cassiterite	Alluvium, sheeted quartz–feldspar veins and pegmatite	Not available
Sybella prospect	10 km south of Mount Isa	Glengarry Resources	Mineralized deeply weathered regolith over granitic rare-metal pegmatite	Columbite–tantalite	Beryl	Regolith materials, pegmatite	Not available

SOURCES: Georgetown, Homestead, Mount Carbine, Sybella prospects — Minmet Ozmine (2002d)
Mistake Creek prospect — Tantalum Australia NL (2002b)

Table 29. Significant tantalum mineralization in Victoria

Mine/deposit/ prospect	*Location/site*	*Exploration/ mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Reserves/resources/ grades*
Walwa Alwa South deposit, The Bounce deposit, Redbank prospect	80 km east-northeast of Wodonga	Tantalum Australia	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, alluvium	Inferred Ta_2O_5 resources: Alwa South: 0.07 Mt at 0.020% The Bounce: 0.27 Mt at 0.023%
Mount Alwa deposit	80 km east-northeast of Wodonga	Tantalum Australia	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Cassiterite	Pegmatite, alluvium	Inferred resources: 6.99 Mt at 0.006% Ta_2O_5 and 0.157% Sn

SOURCE: Tantalum Australia NL (2002c)

A first-stage drilling program of 78 holes in the Walwa area produced some encouraging results. At Alwa South prospect, resources were estimated at about 0.07 Mt at 0.020% Ta_2O_5, and about 0.27 Mt at 0.023% Ta_2O_5 were estimated for The Bounce prospect. No drilling has taken place on the Redbank prospect, as access agreements are still pending. However, results from past exploration at Redbank indicate the presence of at least two thin veins at least several hundred meters in length, and average grades of about 0.015% Ta_2O_5 (Tantalum Australia NL, 2002c).

In 2002, Tantalum Australia extended its regional reconnaissance program to include a geochemical rock-chip survey over the adjoining Mount Alwa, Mount Alfred, and Burrowye exploration areas, and also across the Murray River to the Jingellic area in New South Wales. Samples assaying up to 0.037% Ta_2O_5 were collected from unspecified sites during this survey.

The survey indicated that where these pegmatites contain greater than 0.008% Ta, the Ta:Nb ratio is about 2:1. It was also observed that the Palaeozoic Walwa pegmatites are not as fractionated as some of the Archaean pegmatites from Western Australia. However, the range of alkali metals present is quite similar to the alkali metals present at the Dalgaranga tantalum deposit in central Western Australia. Currently, further exploration in the area is on hold pending access agreements to freehold land (Tantalum Australia NL, 2002b).

Mount Alwa

To date, the most prospective area for tantalum in the Walwa district is located at the old Mount Alwa tin mine, which operated between 1962 and 1968. In 1985, exploration conducted by Golden Eagle Mining resulted in a pre-resource estimate of 8.6 Mt at approximately 0.016% Sn and 0.005% Ta_2O_5 (Simpson et al., 2001). Further work at Mount Alwa by Tantalum Australia in 2001 provided an inferred resource estimate of 6.99 Mt at 0.157% Sn and 0.006% Ta_2O_5, which is equivalent to about 442 t of high-grade Ta_2O_5 concentrate (Tantalum Australia NL, 2002c).

Chapter 12

Tantalum resources of Western Australia

Current exploration and mining

This chapter describes the tantalum deposits and prospects in Western Australia currently in production or under investigation, as well as those tantalum properties that have been in production or have been subject to prospectivity and feasibility studies in recent years. These deposits and prospects are summarized in Table 30.

Other tantalum deposits, prospects, and occurrences in the State that have not been subject to any significant exploration activity in the recent past, and for which little information is available, are listed in Appendix 3. This appendix lists additional tantalum deposits with a history of mining operations, together with more recent estimates of available resources. Although many of these tantalum prospects and localities have been assessed as relatively minor, there are many others that remain largely unexplored.

The location of tantalum mines, deposits, prospects, and occurrences in the State are shown on Plate 1.

Capricorn Orogen

Yinnietharra

Sweetapple (2000) identified the Yinnietharra pegmatites at Arthur River, Beryl Hill, and Camel Hill as belonging to Cerny's simple beryl-type classification for rare-element pegmatites as shown in Table 8.

Arthur River

The Arthur River deposit is located about 212 km east-northeast of Carnarvon in the pegmatite-rich Yinnietharra area of the Gascoyne region in the central-western part of the State. In this area, numerous zoned pegmatites are present within the Palaeoproterozoic Morrissey Metamorphic Suite, a northwest-trending trough-shaped structure composed mainly of metasedimentary rocks that have been extensively migmatized. This unit is also host to numerous Palaeoproterozoic granite intrusions (Fig. 53).

At Arthur River a north-trending, subvertically dipping pegmatite swarm about 700 m in length, containing individual pegmatites of 1–20 m width, is hosted by gneissic and schistose metasedimentary rocks.

In the past, there have been several periods of tantalite mining at Arthur River, with the last one in 1979–80 during a period of high tantalite prices (Fig. 44). At that time, high-grade pods of eluvial tantalite were mined and yielded about 3 t of tantalite concentrates assaying 48.0% Ta_2O_5 and 10% Nb_2O_5 (Equs, 1999).

Commencing in 1988, Rare Resources carried out several exploration programs involving mapping, sub-surface sampling, and shallow auger drilling of a kaolinized pegmatite in an area where very large columbite crystals (up to 360 kg) had previously been discovered. Recovered samples assayed 60.7% Nb_2O_5 and 4.9% Ta_2O_5, and the average grade was estimated at 1.36% Nb_2O_5 and 0.11% Ta_2O_5 (Kanowna Lights Limited, 2000).

During 2000–01, the Arthur River area was explored by Kanowna Lights in a joint venture with Rare Resources. In its first year, Kanowna Lights carried out an extensive geochemical sampling program in the alluvial sediments and eluvial slopes downslope of the Arthur River pegmatites. Results from this survey provided an indicated tantalum resource of about 60 500 t at 0.030% Ta_2O_5 in regolith and placer deposits (Kanowna Lights Limited, 2001a).

In late 2000, the company drilled 51 reverse-circulation drillholes in the hard-rock pegmatites. The most significant result from this program was 0.030% Ta_2O_5 and 0.128% Nb_2O_5 over 2.0 m. A follow-up drilling program in March 2001 provided sufficient data to estimate an unspecified hard-rock resource containing about 11.3 t Ta_2O_5 (Kanowna Lights Limited, 2001b).

In October 2001, Kanowna Lights completed a 100 000 tpa concentrate plant and associated facilities at Arthur River. The plant operated for only one month before being placed in care-and-maintenance while the company continued negotiations with interested parties to secure a long-term off-take agreement. This situation continued until the third quarter of 2002 when the company announced that it had sold its 70% interest in the project to Rare Resources, current holders of the remaining 30% (Kanowna Lights Limited, 2002a).

Negotiations on ownership continued until March 2003, when it was announced that Tantalum Australia, subject to shareholder approval, would take full control of Rare Resources' Yinnietharra alluvial and eluvial columbite–tantalite properties, including the Arthur River deposit and Beryl Hill prospect (MiningNews.net, 2003b).

Table 30. Significant tantalum mineralization in Western Australia

Mine/deposit/prospect	*Location* *Latititude (S)*	*Longitude (E)*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Estimated reserves/ resources/grades*
CAPRICORN OROGEN								
Yinnetharra								
Arthur River deposit	24°38'23"	115°45'28"	Tantalum Australia	Granitic rare-metal pegmatite, regolith, placer	Columbite–tantalite	Beryl	Pegmatite, eluvial and alluvial materials	Indicated placer resource: 60 500 t at 0.030% Ta_2O_5. Hard-rock tantalite resource: 11.3 t Ta_2O_5
Beryl Hill prospect (Cairn mining centre)	24°30'38"	116° 04'03"	Tantalum Australia	Granitic rare-metal pegmatite, regolith, placer	Columbite–tantalite	Muscovite, beryl, quartz, albite, microcline, tourmaline, REE, bismutite	Pegmatite, unconsolidated eluvial and alluvial material	Drilling results up to 0.047% Ta_2O_5 and 0.120% Nb_2O_5
Camel Hill prospect	24°37'22"	116°23'19"	Glengarry Resources	Granitic rare-metal pegmatite	Euxenite	Beryl, uranium mineralization	Pegmatite	Stream-sediment samples up to 0.029% Ta_2O_5
HALLS CREEK OROGEN								
Brockman deposit	18°19'15"	127°47'00"	Aztec Resources/ Tantalum Australia joint venture	Subalkaline granite, syenite (trachyte)	Columbite–tantalite	Zircon, gel zircon, yttrium-bearing REE niobates, albite, K-mica, quartz, fluorite	Altered trachytic tuff	Measured, indicated, and inferred resources: 49.3 Mt at 0.027% Ta_2O_5, 0.44% Nb_2O_5, 1.04% ZrO_2, 0.124% Y_2O_3, 0.090% REE
PILBARA CRATON								
Pilgangoora								
Pilgangoora Alluvials deposit	21°03'05"	118°52'45"	Sons of Gwalia/ Haddington Resources	Placer and regolith deposits	Columbite–tantalite	Cassiterite	Alluvial sands and eluvial material	0.4 Mm^3 sand containing 19.05 t Ta_2O_5
Eastern Pegmatite deposit	21°02'32"	118°54'45"	–	Granitic rare-metal pegmatite	Columbite–tantalite, microlite, tapiolite	Lepidolite, spodumene, cassiterite	Pegmatite	0.25 Mt at 0.027% Ta_2O_5 and 1.3% Li_2O
Tabba Tabba – Strelley								
Tabba Tabba deposit	20°40'00"	118°55'23"	Sons of Gwalia/ Tantalum Australia	Granitic rare-metal pegmatite, regolith, placer	Columbite–tantalite, simpsonite, microlite	Cassiterite, beryl, albite, microcline, quartz, lepidolite,	Pegmatite, eluvial and alluvial materials	Total indicated resources: 0.093 Mt at 0.018% Ta_2O_5
Strelley prospect	20°36'00"	118°58'30"	Sons of Gwalia	Granitic rare-metal regolith, placer	Columbite–tantalite, microlite, tapiolite	Beryl, cassiterite, lepidolite, quartz, microcline	Pegmatite, eluvial and alluvial materials	Remaining resources probably small
Wodgina								
Mount Francisco prospect	21°22'31"	118°32'43"	Sons of Gwalia	Granitic rare-metal pegmatite	Manganotantalite–manganocolumbite, tanteuxenite	Beryl, lepidolite, cassiterite, albite, quartz, microcline	Pegmatite	Not available

Table 30. (continued)

Mine/deposit/prospect	*Location* Latititude (S)	Longitude (E)	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Estimated reserves/ resources/grades*
West Wodgina prospect	21°10'04"	118°38'51"	Sons of Gwalia	Granitic rare-metal pegmatite	Columbite–tantalite	Cassiterite, lepidolite, garnet, tourmaline	Pegmatite	Hard rock resources: 0.044 Mt at 0.13% Ta_2O_5
Wodgina operating mine (Mount Cassiterite and Mount Tinstone)	21°10'52"	118°40'35"	Sons of Gwalia	Deeply weathered regolith over rare-metal granitic pegmatite	Wodginite, tapiolite, manganotantalite, manganocolumbite, microlite, calciotantantite	Cassiterite, albite, spodumene, quartz, microcline, muscovite	Deeply weathered kaolinized pegmatite	Proven and probable reserves: 63.5 Mt at 0.037% Ta_2O_5. Measured and indicated resources: 23.0 Mt at 0.018% Ta_2O_5
Wodgina Alluvials (mine not operating)	21°09'42"	118°40'52"	Reynard Australia	Regolith, placer	Manganotantalite, wodginite, microlite	Iron oxides, cassiterite	Eluvial and alluvial material	Inferred resources: 0.059 Mt at 0.080% Ta_2O_5
YILGARN CRATON								
Bald Hill – Binneringie								
Bald Hill operating mine	31°30'56"	122°10'46"	Haddington Resources	Granitic rare-metal pegmatite	Columbite–tantalite, ixiolite, microlite, wodginite	Cleavelandite, quartz, muscovite, spodumene, cassiterite, beryl	Pegmatite, partially weathered to kaolinite	Measured, indicated, and inferred resources: 2.0 Mt at 0.038% Ta_2O_5
Binneringie deposit	31°30'42"	122°09'31"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite, microlite, ixiolite, tantite	Cleavelandite, spodumene, Li-rich muscovite, quartz, K-feldspar, amblygonite, cassiterite	Pegmatite	Total resource: 1.52 Mt at 0.015% Ta_2O_5 Drilling (2001): 8 m at 0.018% Ta_2O_5 and 12 m at 0.028% Ta_2O_5
Cattlin Creek								
Cattlin Creek deposit	33°33'50"	120°02'23"	Haddington Resources	Granitic rare-metal pegmatite	Columbite–tantalite, microlite	Spodumene, albite, quartz, microcline, muscovite, lepidolite, amblygonite, beryl	Pegmatite	In-pit resource: 0.17 Mt at 0.054% Ta_2O_5
North Ravensthorpe deposit	33°33'33"	120°02'38"	Galaxy Resources	Granitic rare-metal pegmatite	Columbite–tantalite, microlite	Albite, quartz, spodumene, muscovite, lepidolite	Pegmatite	Measured and indicated resources: 0.85 Mt at 0.039% Ta_2O_5. Inferred resources: 0.21 Mt at 0.035% Ta_2O_5
Cobalark prospect	26°47'26"	119°02'25"	Quantum Resources	Granitic rare-metal pegmatite	Columbite–?tantalite	Feldspar, muscovite	Deeply weathered regolith, pegmatite	Grab samples: 0.017% and 0.007% Ta_2O_5, 0.172% Nb_2O_5, 0.024% SnO_2

Table 30. (continued)

Mine/deposit/prospect	*Location* *Latititude (S)*	*Longitude (E)*	*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Estimated reserves/ resources/grades*
Cocanarup prospects	33°41'10"	119°53'11"	Galaxy Resources	Granitic rare-metal pegmatite	Columbite–tantalite, manganocolumbite	Tourmaline, quartz, albite, lepidolite, K-feldspar, muscovite, zinnwaldite, amblygonite	Pegmatite	0.025% Ta_2O_5 (channel sample)
Dalgaranga								
Breakaway deposit	27°42'44"	117°15'39"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Albite, kaolinite	Deeply weathered pegmatite	Estimated resource: 0.13 Mt at 0.014% Ta_2O_5
Dalgaranga operating mine	27°42'38"	117°13'03"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Albite, cleavelandite, muscovite	Pegmatite	Deposit almost worked out. Drilling of downdip extension in 2002 yielded 6.0 m of pegmatite at 0.028% Ta_2O_5
Niobe deposit and Niobe East prospect	27°42'26"	117°16'01"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Albite, zinnwaldite, muscovite	Pegmatite	Measured resource: 57 550 t at 0.024% Ta_2O_5 plus low-grade dumps of 36 000 t at 0.31% Ta_2O_5
Tantalus prospect	27°28'05"	117°08'56"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Albite, cleavelandite muscovite	Pegmatite	Large low-grade Ta_2O_5 resource
Greenbushes operating mine	33°51'27"	116°03'19"	Sons of Gwalia	Granitic rare-metal pegmatite	Tantalite, stibiotantalite, microlite, tapiolite, wodginite, holtite	Cassiterite, albite, quartz, muscovite, tourmaline, apatite, zircon, microcline, spodumene	Pegmatite	Proven and probable reserves: 88.6 Mt at 0.022% Ta_2O_5. Measured, indicated, and inferred resources: 135.1 Mt at 0.022% Ta_2O_5
Londonderry								
Tantalite Hill prospect	31°05'50"	121°04'31"	Plato Mining	Granitic rare-metal pegmatite	Columbite–tantalite, ixiolite	Albite, quartz, garnet, microcline, zinnwaldite, lepidolite, petalite	Pegmatite	Drilling results: 0.008% Ta_2O_5 and 0.045% Li_2O over 4.0 m
Mount Deans deposit	32°18'25"	121°47'06"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Cleavelandite, lepidolite, quartz, beryl, zinnwaldite, cassiterite, tourmaline, petalite, fluorite, spodumene	Pegmatite	Indicated and inferred resources: 9.1 Mt at 0.022% Ta_2O_5, 0.060% Nb_2O_5, 0.170% SnO_2

Table 30. (continued)

Mine/deposit/prospect	*Location*		*Exploration/mining company*	*Deposit style*	*Tantalum minerals*	*Other minerals*	*Host rock*	*Estimated reserves/ resources/grades*
	Latititude (S)	*Longitude (E)*						
Mount Weld deposit	28°51'15"	122°33'20"	Lynas Corporation	Mineralized deeply weathered regolith over carbonatite	Pyrochlore, crandallite	Apatite, florencite and REE, magnetite, vermiculite, smectite clays	Primary carbonatite, secondary enrichment in palaeolake sediments	Inferred resources: 145 Mt at 0.034% Ta_2O_5, 273 Mt at 0.9% Nb_2O_5
Paynes Find								
Mount Edon North prospect	29°18'26"	117°41'00"	Haddington Resources	Granitic rare-metal pegmatite, placer	Columbite–tantalite	Rubidium- and Li-enriched mineralization	Pegmatite	Drilling results: 14 m at 0.010 – 0.028% Ta_2O_5 + Nb_2O_5. Highest value: 0.034% Ta_2O_5 over 1.0 m
Yalgoo								
Johnsons Well deposit	28°13'00"	116°41'00"	Tantalum Australia	Granitic rare-metal pegmatite	Columbite–tantalite	Cleavelandite, lepidolite, muscovite	Pegmatite	High-grade resource: 32 000 t at 0.032% Ta_2O_5. Total resources: 0.13 Mt at 0.019% Ta_2O_5

SOURCES: Capricorn Orogen — Kanowna Lights Limited (2002b); Glengarry Resources Limited (2001d)
Halls Creek Orogen — Ramsden et al. (1993); Minmet Ozmine (2002e)
Pilbara Craton — Sweetapple et al. (2001a,b); Blockley (1980); Hickman (1983); Minmet Ozmine (2002f); Sons of Gwalia Ltd (2002a, 2003); Haddington Resources Limited (2003)
Yilgarn Craton — Hatcher and Clynick (1990); Haddington International Resources (2001); Tantalum Australia NL (2002b); Galaxy Resources (2002); Minmet Ozmine (2002f); Sons of Gwalia Ltd (2002a, 2003); Haddington Resources Limited (2003)

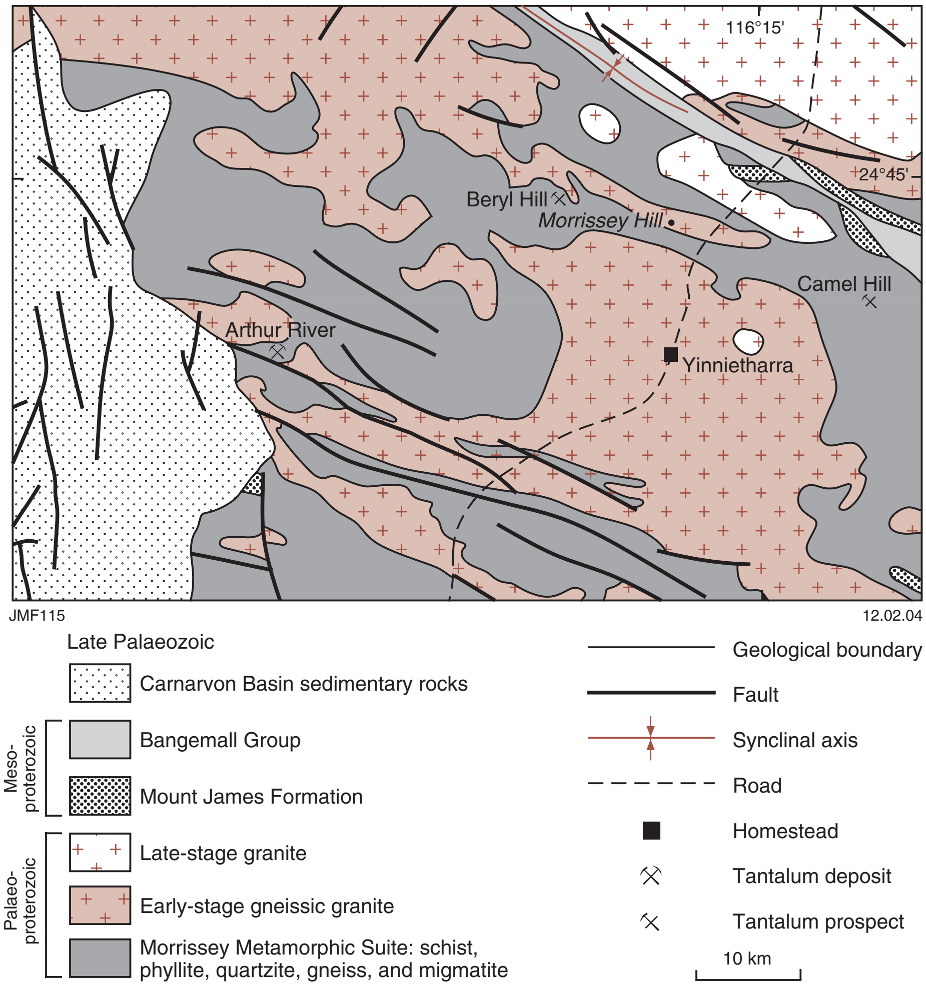

Figure 53. Geological map of the Yinnietharra area (modified from Williams et al., 1983)

Beryl Hill

Beryl Hill (also known as the Cairn mining centre) is located approximately 240 km east-northeast of Carnarvon in the Yinnietharra region of the State. At the Beryl Hill prospect, zoned pegmatites are present in migmatized metasedimentary rocks of the Palaeoproterozoic Morrissey Metamorphic Suite adjacent to a number of granite intrusions (Fig. 53). The pegmatites contain many rare metals, principally niobium and tantalum (columbite–tantalite), beryllium (beryl), bismuth, and tungsten. Pegmatites in this area have average outcrop dimensions of about 150 × 20 m to a maximum of 500 × 50 m at Beryl Hill.

Mining for bismuth, mica, and columbite–tantalite has been carried out intermittently at this site since at least the 1930s and initially continued until the late 1940s. During that time, production of tantalum and niobium from the area amounted to 1.21 t derived entirely from eluvial deposits adjacent to muscovite- and beryl-bearing pegmatite. However, it was in 1979 that the greatest period of mining activity took place when Pilgan Mining (an associate of Greenbushes Tin) produced an estimated 14 t at 30–40% Ta_2O_5 from unconsolidated eluvial material on the northern slopes of Beryl Hill. This campaign was short-lived, as mining came to a halt with the crash in the tantalum price in 1980 (Fig. 44; Kanowna Lights Limited, 2000).

In 1980, at the end of the mining boom, it was noted that there was considerable potential for additional tantalite resources in the numerous pegmatite outcrops on the crest and sides of Beryl Hill, from which the previously mined eluvial tantalite deposits were derived. Current project owners, Rare Resources, have been exploring in the area for 10 years, mainly evaluating eluvial and alluvial pods and lenses of tantalite and columbite.

In 1999 the company, in a joint venture with Border Gold, drilled 28 reverse-circulation drillholes to test the mineralized pegmatite situated above the site of the eluvial tantalite deposits worked in 1979–80. Interpretation of drillhole data showed the pegmatite to be a tabular, flat-lying structure up to 94 m thick. Analysis of drill samples provided some encouraging results, with values up to 0.047% Ta_2O_5 and 0.120% Nb_2O_5. No further exploration appears to have taken place at Beryl Hill since that time (Kanowna Lights Limited, 2000).

As mentioned previously, Tantalum Australia announced on 22 March 2003 that it had acquired 100% of the Beryl Hill prospect from Rare Resources.

Camel Hill

The Camel Hill exploration area is located about 35 km east-southeast of Beryl Hill (Fig. 53). In this area, Glengarry Resources has taken out an exploration licence covering most of the Mortimer Hills, including the area surrounding Camel Hill. As is the case at Beryl Hill, this area also consists mainly of migmatized metasedimentary rocks of the Palaeoproterozoic Morrissey Metamorphic Suite, as well as numerous small granite intrusions. There are numerous pegmatites located within the migmatite. Many of these pegmatites are sites of small beryl prospects mined between 1943 and 1962. Many of the pegmatites contain small quantities of the yttrium- and cerium-rich tantalum mineral euxinite, as well as rare earths, bismuth, and uranium mineralization (Williams et al., 1983).

In 2001, Glengarry Resources carried out stream-sediment sampling in the area to confirm tantalum stream-sediment anomalies obtained in a previous Government geochemical-sampling program (Sanders et al., 1997). Glengarry's sieved stream-sediment samples yielded tantalum values up to 0.029% Ta_2O_5 and panned tantalum concentrates up to 0.191% Ta (Glengarry Resources Limited, 2001e).

The company also located a northwest-trending zone, 10 km long by 3 km wide, containing tantalum stream-sediment assays greater than 25 ppm. This trend coincides with a previously unexplored granite–metasedimentary rock contact zone. To date, no further work has taken place in the exploration area.

Halls Creek Orogen

Brockman

The Brockman polymetallic deposit, located 18 km southeast of Halls Creek in the east Kimberley region and discovered in 1982, is perhaps Western Australia's most unusual style of tantalum–niobium mineralization. Union Oil Development Corporation and West Coast Holdings carried out an extensive program of percussion and diamond drilling over the deposit to an average depth of 70 m, with the deepest hole reaching 250 m. Evaluation of drillhole data and analytical results resulted in an estimated measured resource in situ of 4.29 Mt, together with indicated and inferred resources of 45 Mt, with all resources grading 0.027% Ta_2O_5, 0.440% Nb_2O_5, 1.040% ZrO_2, 0.124% Y_2O_3, 0.090% rare earths, plus 350 ppm hafnium and 110 ppm gallium (Aztec Resources Limited, 2001a).

Mineralization in the Brockman deposit is hosted by a hydrothermally altered trachyte that forms part of the Butchers Gully Member of the Palaeoproterozoic Olympio Formation (Blake et al., 1999). Geological mapping has shown that the resource is contained within a vertical or steep easterly dipping trachytic ash-flow tuff (known as the 'niobium tuff') that is 5–35 m wide and extends over a strike length of 3.5 km (Fig. 54).

Studies carried out by CSIRO (Ramsden et al., 1993), have shown that the niobium tuff actually comprises two pyroclastic units of roughly equal thickness that appear to have been deposited within a short time of each other and cooled as a single unit. The initial lower unit was a pyroclastic ash-flow eruption composed of crystal-rich magma enriched in incompatible elements and fluorine, and containing albite and potassium mica. The upper unit was a pyroclastic pumice-rich eruption also enriched in incompatible elements and containing mainly microcrystalline potassium mica and quartz. During the cooling phase, alteration and remobilization of the deposit was effected by fluorine-enriched hydrothermal fluids trapped within the unit reacting with precursor minerals such as columbite and zircon to form ore-grade mineralization.

Ramsden et al. (1993) determined that the nature of the trachytic magma from which the deposit originated is problematical in that it contains no feldspathoids or ferromagnesian minerals (or their alteration products), despite the high content of incompatible elements typical of peralkaline magmas. The major-element chemistry and normative mineralogy compositions demonstrate their inconsistency with peralkaline magmas by plotting within the subalkaline field of a ternary K–Na–Al diagram.

These facts suggest that the style of occurrence of the Brockman mineralization is somewhat unusual in as far as it does not match the more common peralkaline granite–syenite and metasomatite mineralization style for tantalum deposits (Fig. 7). Accordingly, the provisional classification of subalkaline granite–syenite is suggested for the Brockman deposit.

Electron microprobe studies have shown the ore minerals to be very fine grained, with the majority of grains being less than 10 μm in diameter. Principal ore minerals include zircon, gel-zircon, columbite, and yttrium-bearing rare-earth niobates. Columbite is present in extremely fine grains of 1–2 μm diameter. In the niobium-rich – tantalum-poor columbite, tantalum is present in the ratio of 1:15 (Aztec Resources Limited, 2001b).

Recent project owners, Aztec Resources, have been developing a process flowsheet following the receipt of a positive consultant report on the project's viability. It is reported that the Brockman ore is of high value, with niobium representing 52% of the value, and tantalum, zirconium, and hafnium each representing 12–14%, with the remainder being rare earths and gallium. Financial modelling has indicated that mining of 1 Mtpa and direct shipment of ore to the port of Derby for chemical extraction may represent the best economic option. A prefeasibility study, mining plan, and schedule also need to be developed to determine the project's overall economics (Aztec Resources Limited, 2002; Winter, 2002).

In March 2003, it was announced that Tantalum Australia had farmed into the Brockman project, together

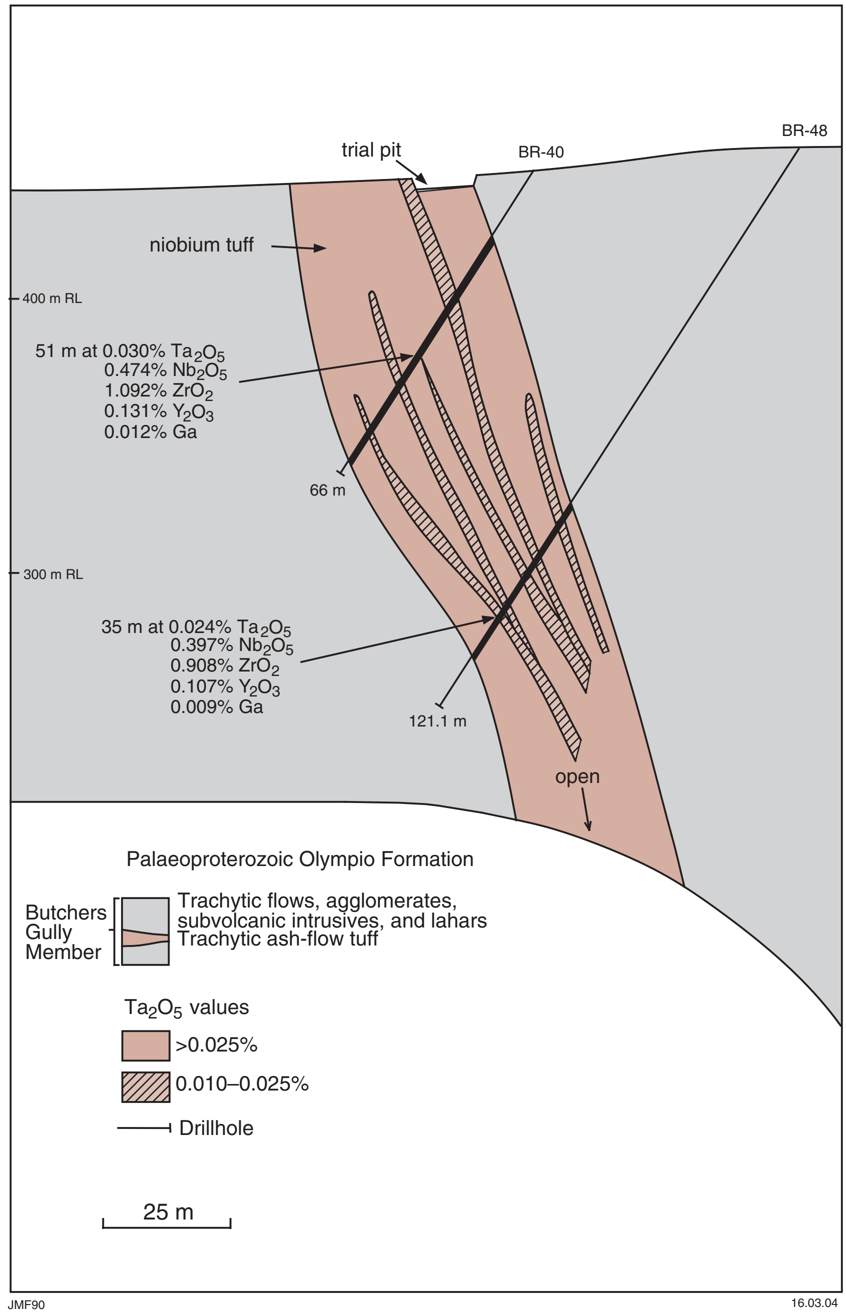

Figure 54. Cross section of the Brockman polymetallic deposit showing drillhole intercepts and mineralization grades (modified from Aztec Resources Limited, 2001a)

with Aztec Resources. In this joint venture, Tantalum Australia can earn a 60% stake in the project by spending \$1.5 million over three years, and then lift their ownership to 78% by spending a further \$2 million over five years (MiningNews.net, 2003b).

Pilbara Craton

Pilgangoora

Pilgangoora is situated on the western side of the McPhee Range, about 82 km south-southeast of Port Hedland. This is an area of north-trending Archaean greenstones known as the East Strelley greenstone belt (Van Kranendonk et al., 2002). In the Pilgangoora area, the greenstones comprise a series of steeply dipping, mafic metavolcanic rocks and amphibolites that are faulted against the Archaean Carlindi Granitoid Complex on the western side.

At Pilgangoora, the greenstones have been intruded by a swarm of north-trending, east-dipping pegmatites extending from Mount York in the south northwards for about 11 km to McPhees mining centre. Many of the pegmatites are very large, reaching over 1000 m in length and 200–300 m in width (Fig. 55). Despite their large size, mineralization within these zoned pegmatites appears to be restricted to alteration zones, mainly along vein margins containing quartz, albite, muscovite, and spessartine garnet. These mineralized zones contain varying amounts of lepidolite, spodumene, tantalite, cassiterite, and minor microlite, tapiolite, and beryl. Mining of four small hard-rock tantalum prospects in the area around Pilgangoora took place in the middle part of the 20th century. In recent years, a number of exploration licences over the area were held by Pilgan Mining in a joint venture with the Lynas Corporation and Prima Resources. Today, most of these tenements have expired.

At Pilgangoora there are also many areas of eluvial and alluvial tin–tantalum mineralization. These are found in and around the streams draining into the Turner River on the western side of the McPhee Range. It was in these regolith and placer deposits that most of the tantalite mining occurred and about 50 t of mixed tantalum–niobium concentrates were extracted between 1947 and 1975 (Blockley, 1980). In 1968, Ishihara Sangyo Kaisha Limited carried out sampling of about 30 creeks and gullies in the area. The survey established resources of about 0.288 Mm^3 of alluvial sediments containing an estimated 220 g/m^3 Ta_2O_5 and 100 g/m^3 of both Nb_2O_5 and SnO_2, using a cut-off grade of 60 g/m^3 (Hickman, 1983).

In recent years, a number of companies have shown an interest in the Pilgangoora area. In 2000, Kanowna Lights drilled over 27 auger holes in areas of tantalum-enriched placer deposits. Drilling confirmed that the coarser fraction of the sediments, including most of the heavy minerals, was deposited close to stream discharge points. The drilling program yielded head grades of 0.0037% Ta_2O_5,, 0.0053% Nb_2O_5, and 0.0046% SnO_2. From these values the company estimated the project area contained 0.4 Mm^3 of treatable sands from placer deposits that contained about 19.05 t of Ta_2O_5.

In 2001, Kanowna Lights also entered into an agreement with Prima Resources and Fieldcorp to acquire the Pilgangoora tailings dump, gravity separation plant (Fig. 32), and camp infrastructure. At the time, Kanowna Lights intended to refurbish the treatment plant before commencing mining and tantalite concentration operations; however, the agreement lapsed in March 2002. Currently, Sons of Gwalia have an application pending for an exploration licence over the area.

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Figure 55. A very large, south-trending pegmatite (about 20 m wide) in the McPhee Range at Pilgangoora (approximate location is Lat. 21°02'55"S, Long. 118°54'26"E)

In November 2001, Haddington International Resources acquired Australian Tantalum. At the time, Australian Tantalum held eleven exploration areas prospective for tantalum in the State, including an area at Pilgangoora. This exploration licence covers an extensive area of alluvial gravels prospective for tantalum placer deposits within the drainage systems to the west of Pilgangoora.

Tabba Tabba – Strelley

The Tabba Tabba and Strelley tantalum prospects are situated in pegmatites intruding an arcuate narrow ridge of north-northeasterly trending Archaean greenstones, about 1–2 km wide and over 75 km long, extending from 50 km southeast to 65 km south of Port Hedland in the Pilbara region. The greenstones, composed of metagabbro, chert, amphibolite, and other ultramafic rocks, dip steeply westwards as part of a regional synclinal structure, and run parallel to a regional shear abutting their eastern boundary. Late-stage post-tectonic granites are present in places on either side of the greenstone belt.

Tabba Tabba

Tabba Tabba is located 50 km southeast of Port Hedland. The main tantalum-bearing pegmatite is 600 m long and varies from 10 to 50 m in width. This strongly zoned pegmatite, hosted by amphibolite, is largely composed of microcline, coarsely crystalline albite, and a massive quartz core (Figs 11–13). Mineralization is restricted to the fine-grained aplitic zone surrounding the core. The innermost mineralized layer is composed of simpsonite, tantalite, and large beryl crystals that penetrate the quartz core in places. Further out is a zone of aplite containing mainly disseminated tantalite. Beyond this are unmineralized zones of quartz–albite–muscovite and microcline. Other minerals found in the mineralized zones include manganotantalite, manganocolumbite, microlite, and cassiterite (Hickman, 1983).

Mining was first recorded at Tabba Tabba as early as 1916, originally for tin, and continued until about the early 1980s. This deposit is probably unique in that it was specifically mined for its lode of simpsonite (an aluminium-rich tantalate mineral; Fig. 56) situated immediately beneath the quartz core, as well as the more common tantalum minerals in the more distant zones (Ellis, 1950). Adjacent to the main pegmatite lodes, secondary eluvial and alluvial deposits were mined for tin and tantalite. Total recorded production from Tabba Tabba is 27.3 t of tantalite and columbite, 131.9 t of cassiterite, and 52.4 t of beryl (Witt, 1990). A detailed account of the geology and past mining activities in the Tabba Tabba area is given in Ellis (1950).

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Figure 56. Simpsonite collected from the mining operations at Tabba Tabba (Simpson Collection, Western Australian Museum)

In 1999, Sons of Gwalia identified two new areas of alluvial mineralization covering about 25 ha. Small-scale alluvial tantalum mining was carried out by the lease owners, K. & C. Thorpe, on a tribute basis for Sons of Gwalia and involved the movement of about 50 000 m^3 of material.

Today, most of the old mining sites at Tabba Tabba have been rehabilitated. Exploration companies currently holding ground at Tabba Tabba are Sons of Gwalia and Tantalum Australia. The area of the Tabba Tabba lode and associated alluvial deposits is currently held by K. & C. Thorpe on a care-and-maintenance basis.

Published figures for the total indicated resources for the Tabba Tabba hard-rock and placer deposits are 0.093 Mt at 0.018% Ta_2O_5 and they are estimated to contain 16.47 t of tantalum metal.

Strelley

Eighteen kilometres north-northeast of Tabba Tabba, the Strelley prospect contains a north-northeasterly trending pegmatite dyke 700 m in length and between 25 and 200 m wide. The dyke appears to have an almost stratiform relationship with the Archaean greenstone host rocks that comprise pelitic schist, ferruginous chert, serpentinite, and amphibolite.

Mineralized zones within the pegmatite are found in greisen lenses, and as stockworks in fine-grained albite replacement of microcline. Principal minerals are manganotantalite, lepidolite, and beryl, as well as small quantities of cassiterite, microlite and tapiolite. However, it should be noted that the largest quantity of tantalite was recovered from colluvial deposits on either side of the ridge containing the pegmatite. Recorded production from Strelley is 24.6 t of tantalite and columbite , 38.6 t of beryl, and 0.1 t of cassiterite (Witt, 1990). A detailed account of the geology and past mining activities in the Strelley area is given in Ellis (1950).

Following limited mining of alluvial deposits that were completed in early 2001, the old workings at Strelley dating back to the early and mid-20th century have largely been rehabilitated. Sons of Gwalia have recently carried out a new prospectivity study of the area, with limited success.

Wodgina

Wodgina mine

In 1902, tantalite orebodies were discovered at the present-day Wodgina mine site, located about 100 km south of Port Hedland in the Pilbara region. Over a period of almost 100 years, these orebodies have been variously worked for tin, tantalum, and beryl. Today, Wodgina is owned and operated by Sons of Gwalia, and the mine maintains its position as the world's second-largest tantalum resource and mining operation. Current total reserves and resources at Wodgina are estimated at 86.5 Mt averaging 0.027% Ta_2O_5 comprising proven and probable reserves of 63.5 Mt at 0.037% Ta_2O_5 estimated to yield over 23 200 t Ta_2O_5, and measured and indicated resources of 23.0 Mt at 0.018% Ta_2O_5 estimated to yield over 3600 t Ta_2O_5 (Sons of Gwalia Ltd, 2002a).

The following description is a summary of the principal features of the two tantalum-bearing pegmatite systems found at Wodgina. A full description of these orebodies is given in Sweetapple et al. (2001b), and Sweetapple and Collins (2002).

The Wodgina Archaean greenstone belt is located on a major north-northeasterly trending, sinistral shear zone. The greenstones are a series of metamorphosed ultramafic rocks (including komatiites), metabasalt, amphibolite, and metasedimentary rocks including chert, and fine-grained psammites with pelitic interbeds. The greenstones are incorporated in a synformal body of about 10 km in an east–west direction and 25 km in a north–south direction that plunges in a north-northeasterly direction (Fig. 57). In the area of the mine site, the regional shear appears to have been displaced about 750 m by a local east-northeasterly trending dextral shear that truncates the Wodgina main-lode pegmatite at its southern end (Fig. 58).

Sweetapple et al. (2001b) has proposed that the Wodgina rare-metal pegmatites were most likely intruded into the greenstone suite at Wodgina through the migration of hydrous residual magmatic phases of cooling local granites that were highly enriched in incompatible elements. It is thought that the marginal leucocratic phase of the Numbana Granite is mainly responsible for this event (Fig. 57). A recent date of 2829 ± 11 Ma obtained by Kinny (2000) for columbite–tantalite mineralization from the Wodgina openpit would appear to indicate a link to the 'younger' 2830–2890 Ma granites of the Yule Granitoid Complex to which the Numbana Granite has been assigned.

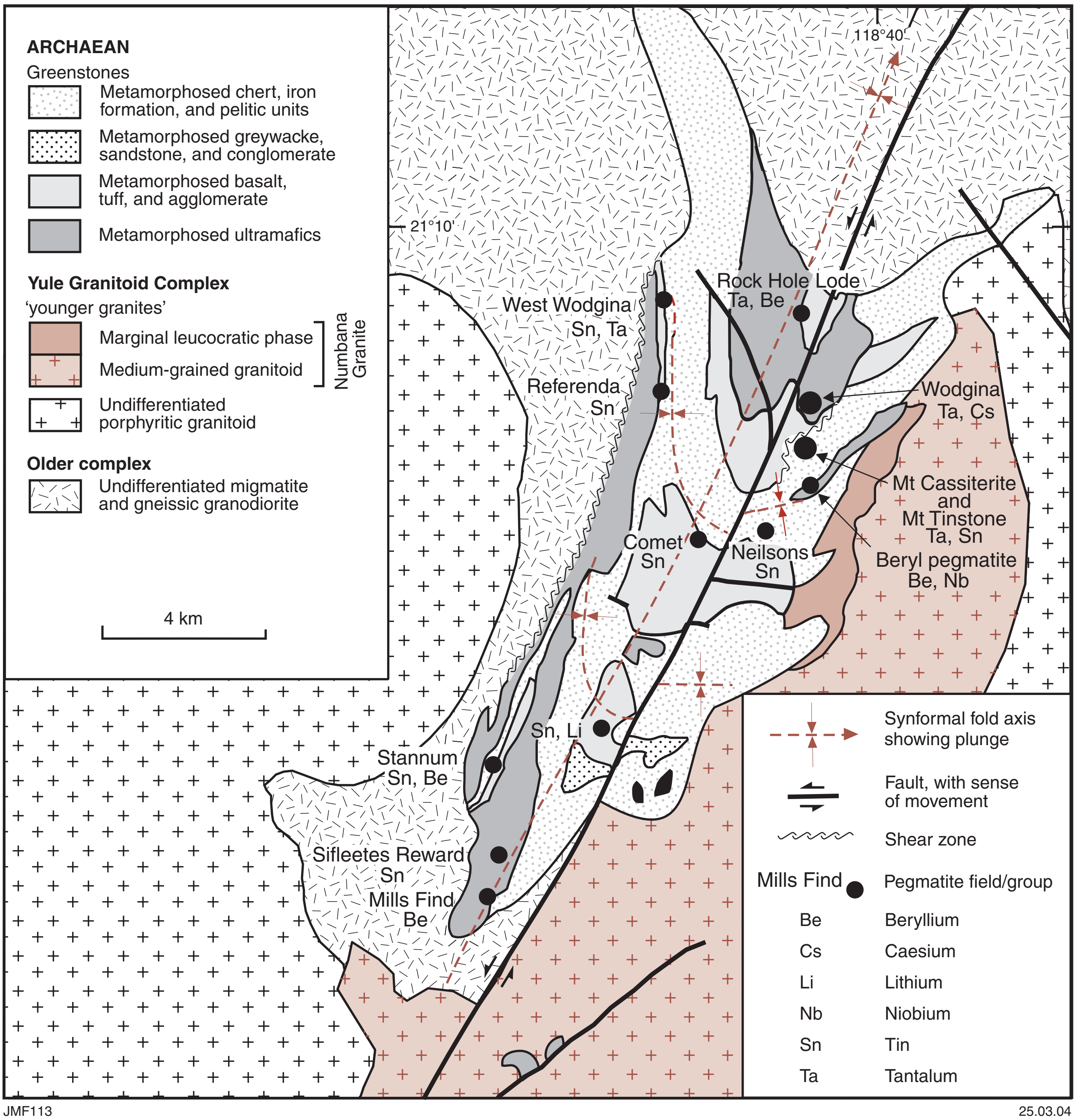

Figure 57. Geological map of the Wodgina greenstone belt (modified from Sweetapple et al., 2001b)

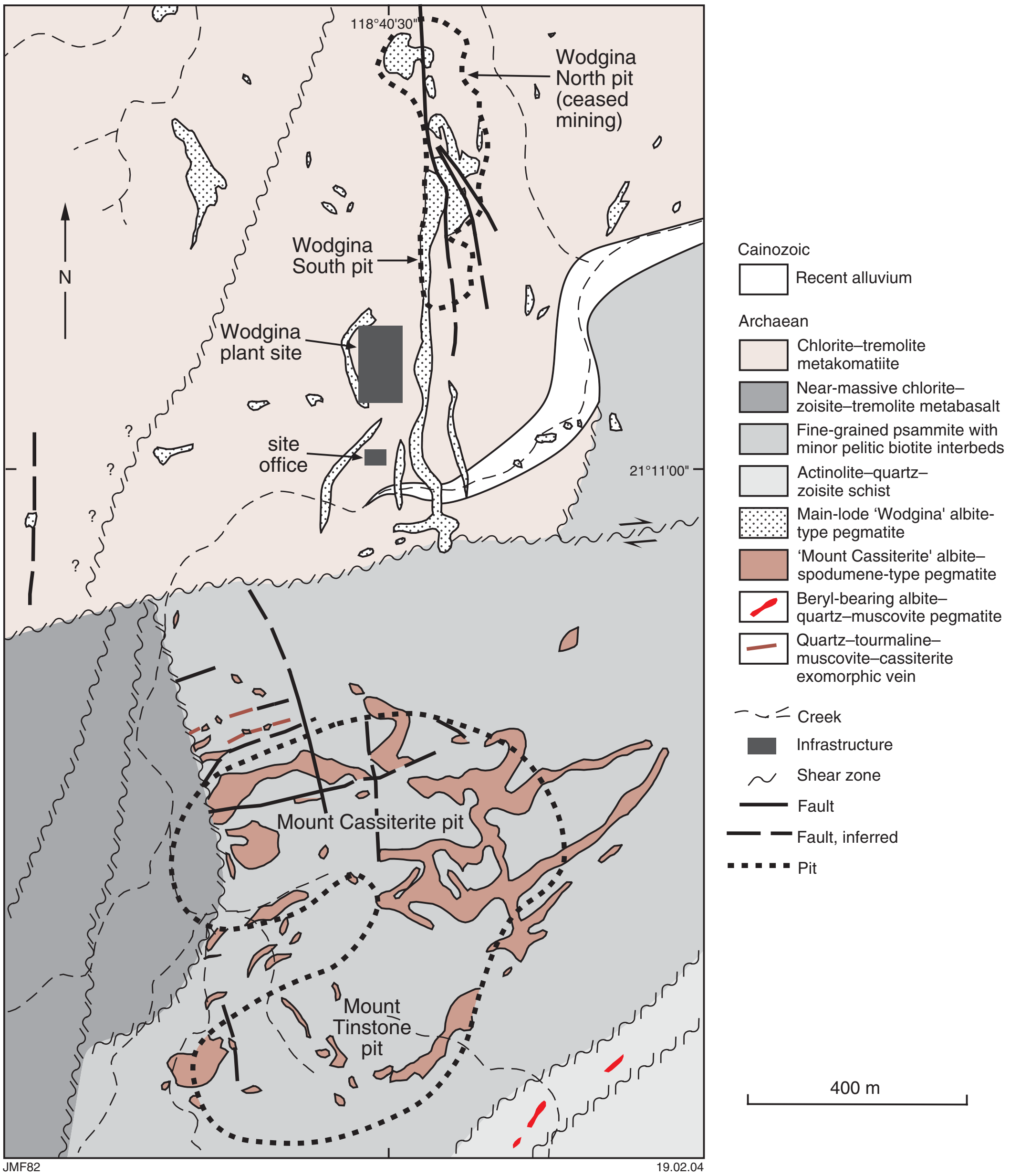

Figure 58. Geological map showing the distribution of pegmatite groups at the Wodgina mine site (modified from Sweetapple et al., 2001b)

Three different pegmatite groups have been recognized at Wodgina. The first of these is an essentially non-mineralized beryl-bearing albite–quartz–muscovite pegmatite located to the southeast of Mount Cassiterite (Fig. 58), and assigned to the simple beryl-type pegmatite group (Table 8).

The second pegmatite group is the strongly layered tantalum-rich Wodgina main-lode pegmatite that intruded the ultramafic chlorite–tremolite metakomatiite sequence in the northern half of the Wodgina mine site area (Fig. 58). This pegmatite is representative of Cerny's albite pegmatite group (Table 8).

The remaining pegmatites belong to the Mount Cassiterite pegmatite group that forms a series of stacked tantalum-rich sheets intruding fine-grained, psammitic metasedimentary rocks with minor pelitic biotite interbeds in the central-southern part of the Wodgina area (Fig. 58). These pegmatites, which form the centre of current mining operations at Mount Cassiterite and Mount Tinstone, are of the albite–spodumene pegmatite group (Table 8).

It should be noted that neither the Wodgina main-lode pegmatite nor the Mount Cassiterite pegmatite group display classical concentric internal-zonation patterns characteristic of highly fractionated pegmatites. Whereas the Wodgina main-lode pegmatite displays an atypical layered zonation pattern, the Mount Cassiterite pegmatite group shows little primary layering or zonation (Sweetapple et al. 2001b).

Wodgina main-lode pegmatite

Until 1984, the Wodgina main-lode pegmatite produced 269 t of tantalum and an inferred production of 44 t of niobium. The deposit also yielded 85 t of beryl to the end of 1945. Large-scale mining of the Wodgina main-lode pegmatite began in 1988 and was based on proven reserves averaging 0.402 Mt at 0.128% Ta_2O_5 and 0.021% Nb_2O_5 (Sweetapple et al., 2001b). Mining continued until 1994, when the deposit was largely worked out.

Host rocks for the Wodgina main-lode pegmatite are mostly a succession of chlorite–tremolite komatiites with minor metabasalt and dolerite (Fig. 59). The emplacement of at least part of the pegmatite appears to have been subject to control by pre-existing folding (Sweetapple et al. 2001b).

The main-lode pegmatite is about 1 km in length and varies from 5 to 40 m in thickness. Previous mining revealed a pegmatite body around a central irregular quartz core measuring 50 m wide by 60 m long. At the southern end, the pegmatite is reduced to a sheet that dips in an easterly direction into a fault zone, whereas at the northern end the body becomes bulbous and saddle-shaped. It was proposed by Sweetapple et al. (2002) that the Wodgina albite-type pegmatite 'has been derived directly from the albite–spodumene Mount Cassiterite pegmatite group, due to the separation of a highly fluxed volatile-enriched melt fraction'.

The well-layered structure and atypical zonation in the pegmatite is best developed at the southern end of the main-lode openpit. Here, massive hangingwall and footwall cleavelandite units are present on either side of an aplitic- to granitic-textured albite–quartz–muscovite pegmatitic central unit, with inclusions of megacrystic microcline and replacement by sugary albite and lithian muscovite. A massive quartz core is present at the northern end (Figs 60 and 61).

In this pegmatite, most of the primary mineralization is contained within the massive cleavelandite units, commonly towards the base or in cleavelandite orbicules, or within sugary albite-replacement zones. Drillhole intercept grades from the pegmatite indicate a range of values from 0.047 to 0.685% Ta_2O_5, with the higher values

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Figure 59. Sharp contact between the massive footwall cleavelandite unit of the Wodgina albite-type pegmatite and the underlying metabasalt host rock at the Wodgina South openpit

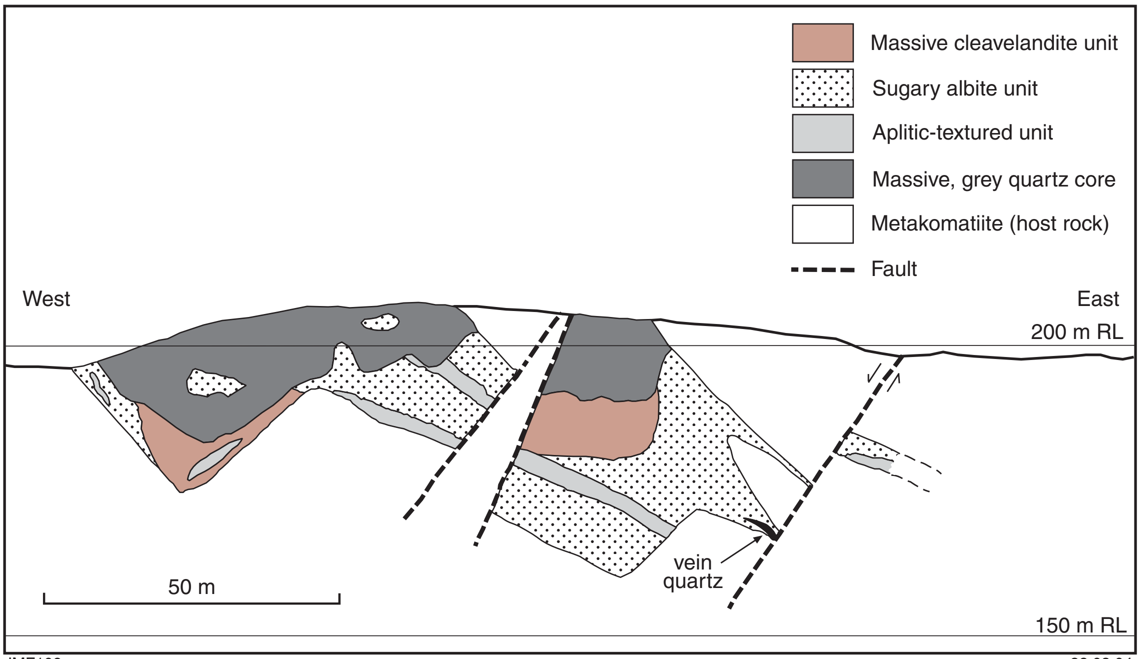

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Figure 60. East–west cross section through the Wodgina South pit. Diagram shows the interpreted internal structure of the Wodgina albite-type pegmatite (modified from Sweetapple et al., 2001b)

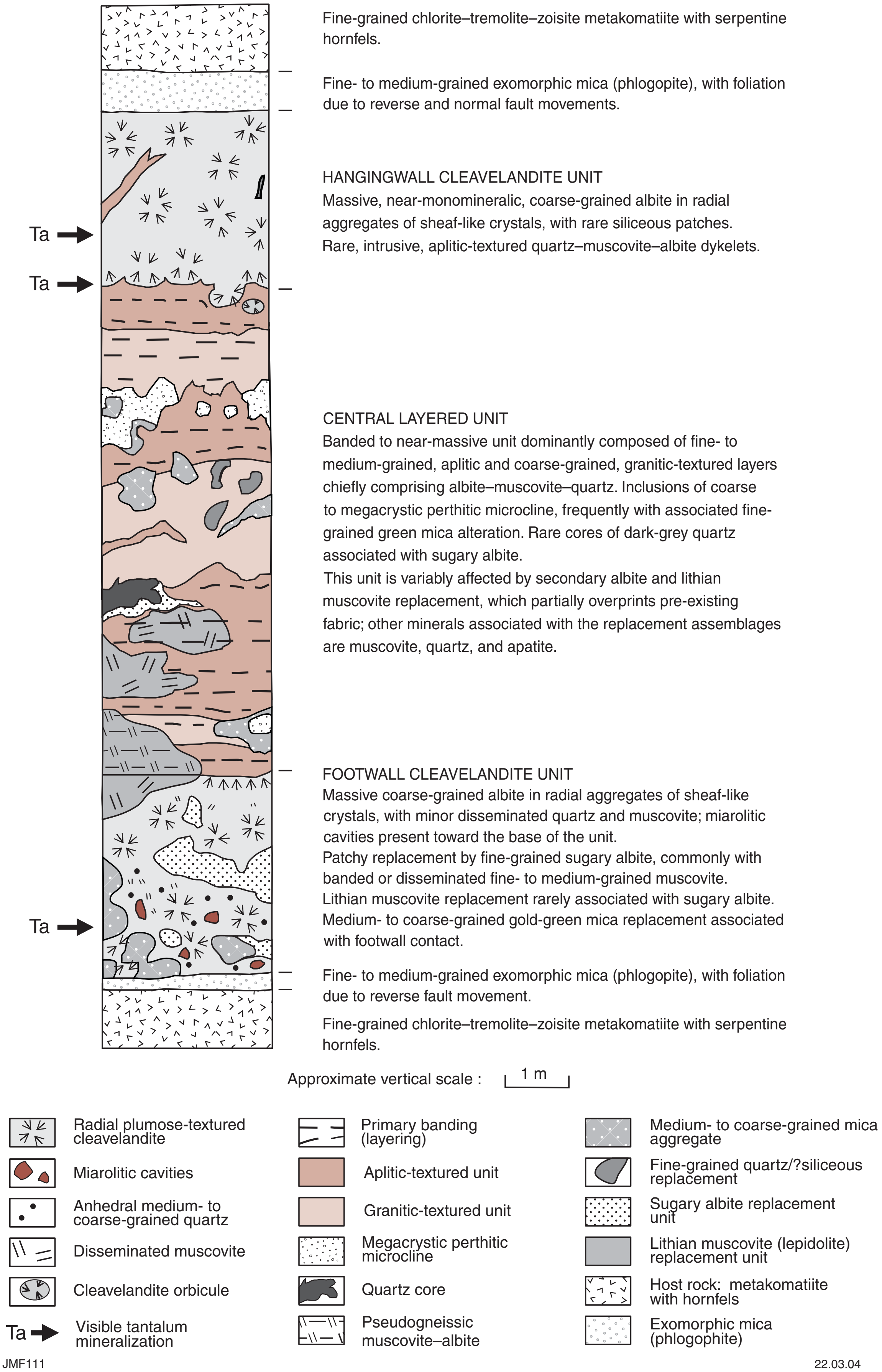

Figure 61. Schematic section showing the atypical zonation layers of the Wodgina albite-type pegmatite in the Wodgina South openpit (modified from Sweetapple et al., 2001b)

consistently in the areas of sugary albite. The primary ore mineral is manganotantalite, with subordinate manganocolumbite and wodginite, and minor microlite and fersmite. There is considerable variation in the size of the tantalum minerals, which range from less than 0.25 mm to very large crystal masses up to 250 kg. However, the bulk of the mineralization is generally fine grained. Figure 61 illustrates sites of visible tantalum mineralization within the hanging and footwall cleavelandite units (Sweetapple et al., 2001b).

Mount Cassiterite and Mount Tinstone

Since 1988, mining activities have shifted to the Mount Cassiterite tantalum–tin pegmatite deposit, and more recently to the adjacent Mount Tinstone deposit. Mining is carried out at both sites simultaneously (Fig. 62). Prior to 1988, the Mount Cassiterite deposit produced 308 t of tantalum, as well as inferred production of 193 t of tin and 39 t of niobium. Wodgina first achieved its status as the world's second-largest tantalum source in the 1997–98 fiscal year when production from Mount Cassiterite reached 77 t of Ta_2O_5, which constituted 7.25% of world production (Sweetapple et al., 2001b).

Host rocks for the Mount Cassiterite pegmatite group in this area are a sequence of metasedimentary rocks comprising fine-grained psammites with pelitic biotite interbeds. These rocks are extremely weathered to at least 80 m below the surface and the pegmatites have been affected by deep weathering to at least 50 m depth, with the feldspars showing varying degrees of kaolinization (Figs 8 and 63–64).

In the area of the interlinked openpits of Mount Cassiterite and Mount Tinstone, there are four stacked pegmatite sheets ranging from 5 to 80 m thick, mostly gently dipping 20–25° to the southeast. The uppermost sheet is the thick, deeply weathered Mount Tinstone sheet (Fig. 64), followed by the thin Hanging Wall sheets, and beneath this is the thick Main sheet at Mount Cassiterite. The lowermost unit, discovered recently in a drilling program, is the Lower sheet. This very large tantalum resource is 50–200 m thick, with the footwall up to 400 m below the surface (Fig. 65).

The three uppermost sheets at Mount Cassiterite and Mount Tinstone are currently mined for high-grade tantalum ore. A representative cross section showing the Hanging Wall and Main sheets at Mount Cassiterite is shown in Figure 66. This diagram shows illustrative Ta_2O_5 grades in drillhole intercepts ranging from 0.022 to 0.103%. The very large Lower sheet has lower Ta_2O_5 grades averaging 0.014% and is expected to be retained as a future tantalum resource.

The Mount Cassiterite pegmatites essentially lack a recognizable zonation pattern, and have a variable texture from massive to weakly layered. The internal structure of one of the pegmatite sheets exposed in the Mount Cassiterite openpit is dominated by a central zone of megacrystic comb-textured spodumene with pull-apart structures, and subordinate megacrystic perthitic microcline concentrated towards the centre of the unit. This texture is a characteristic feature of the albite–spodumene pegmatite group (Sweetapple et al., 2001b). The footwall and hangingwall units comprise weakly layered, fine-grained albite–quartz–muscovite border zones and indistinct bands, concentrations of megacrystic perthitic microcline, and rare, small quartz cores. Sugary albite replacement accompanied by fine-grained muscovite is common throughout the section (Fig. 67).

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Figure 62. View looking south showing pegmatite sheets at Mount Cassiterite (left foreground) and Mount Tinstone (top right)

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Figure 63. Deeply weathered, kaolinized pegmatite and host psammitic metasedimentary rocks at the Mount Cassiterite openpit (looking west)

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Figure 64. Tantalum-rich orebody at Mount Tinstone. Photograph shows an 8 m exposure in the south wall of deeply weathered, kaolinized pegmatite containing a xenolith of psammitic metasedimentary rocks (dark coloured)

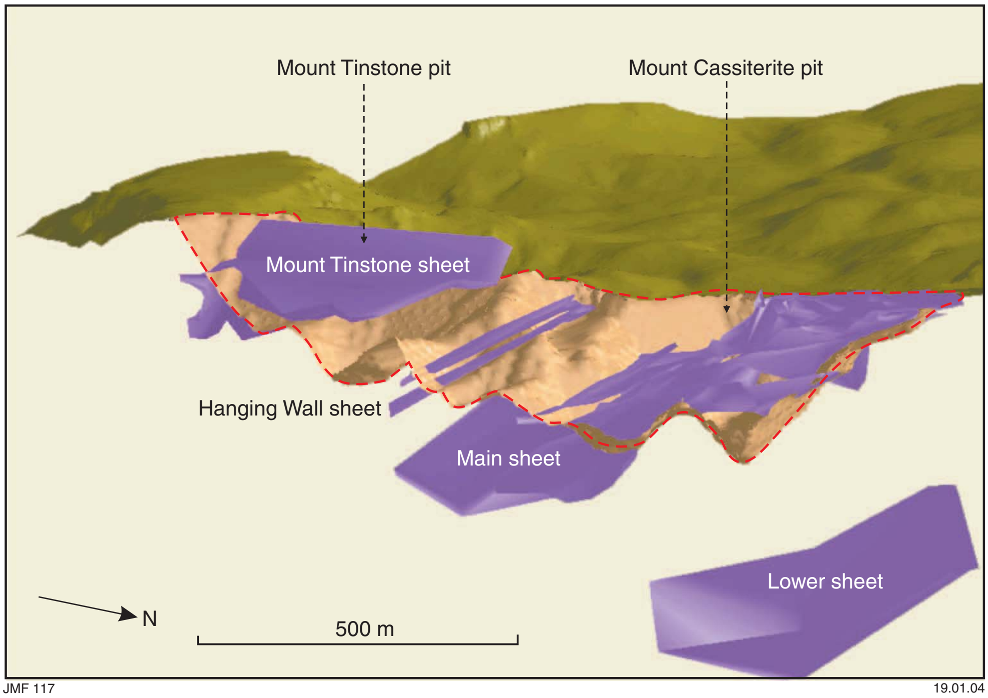

Figure 65. Block diagram showing the distribution of pegmatite sheets at the Mount Cassiterite and Mount Tinstone openpits (modified from Sons of Gwalia Ltd, 2001)

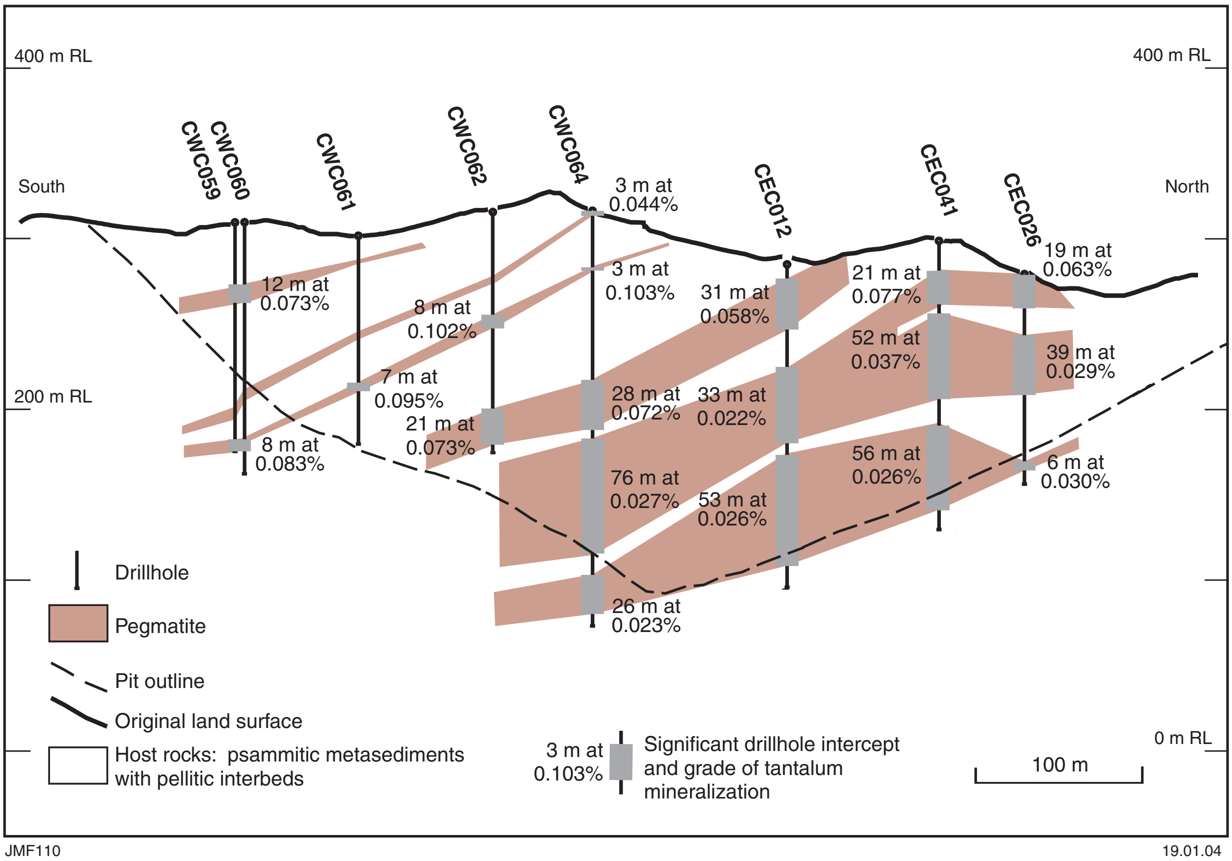

Figure 66. North–south cross section through the Mount Cassiterite openpit. Diagram shows the thin upper Hanging Wall sheets overlying the thick Main sheets of the Mount Cassiterite albite–spodumene-type pegmatite (modified from Sweetapple et al., 2001b)

Figure 67. Schematic section showing the internal texture and composition of the Mount Cassiterite albite–spodumene-type pegmatite in the uppermost pegmatite in the west wall of the Mount Cassiterite openpit (modified from Sweetapple et al., 2001b)

The main ore minerals for the Mount Cassiterite pegmatite group are wodginite, cassiterite, and tapiolite, with subordinate manganocolumbite, manganotantalite with microlite, and traces of calciotantite. Unlike the concentration of mineralization in the massive cleavelandite units of the Wodgina main-lode pegmatite, mineralization in the Mount Cassiterite pegmatite group appears to be more variably distributed throughout the pegmatite sheets, with little internal control on ore distribution except around host-rock and xenolith contacts, where elevated caesium and rubidium values may be present in some of the lower sheets. The grain size for tantalum and tin minerals rarely exceeds 0.5 mm, with the average being in the range of 0.1 – 0.25 mm.

Wodgina Alluvials

Several kilometres downstream, in the drainage catchment leading from the Wodgina hard-rock tantalum mine, are alluvial workings that have been operated by Reynard Australia. It is understood that this deposit was worked until early 2002, when the portable alluvial concentration plant was mothballed due in part to lack of water for concentrate processing. When in operation, feed material for the plant was apparently obtained from around the site and from a number of other local alluvial and eluvial sources around Wodgina (Fig. 30).

Chemical analysis of the heavy concentrate produced by the plant (Fig. 31) indicates that it is principally composed of iron oxide (66.01% Fe_2O_3), together with tin (11.07%), tantalum (5.78%), and niobium (1.02%). X-ray powder diffraction analysis shows the tantalum mineralogy to consist mainly of a mixture of partially disordered manganotantalite, wodginite, and microlite.

Inferred resources for this deposit are estimated at 0.059 Mt at 0.080% Ta_2O_5, with a contained metal content estimated at 47.20 t (Department of Industry and Resources, 2003).

West Wodgina

The area about 4 km west-northwest of the Wodgina mine on the western side of the Wodgina range is known as West Wodgina (Fig. 57). This is an area of tin mining that commenced production early in the 20th century. Past production from small alluvial deposits in the area amounted to 8.03 t of cassiterite and 1.11 t of tantalite (Hutton, 1982).

West Wodgina is an area of Archaean greenstones comprising amphibolite schist, ultramafic rocks, and siliceous metasedimentary rocks that are intruded by both simple and zoned pegmatite veins. Mineralization in these pegmatites includes cassiterite, lepidolite, garnet, and tourmaline. Production from the West Wodgina mine was small and consisted of only a few tonnes of tin concentrate. More recent hard-rock resources have been estimated at 0.044 Mt at 0.13% Ta_2O_5.

About 10–12 km further south are the tin mines of Stannum and Mills Find. At Stannum, low-dipping, narrow pegmatite veins less than 1 m wide contain cassiterite (up to 5% SnO_2), columbite, lepidolite, tourmaline, and topaz. It has been reported that the Stannum mines were responsible for the production of about 11.1 t of tin concentrate, whereas a parcel of ore from Mills Find yielded 0.7 t of tin concentrate from 20 t of pegmatite at 3.5% SnO_2 (Blockley, 1980).

Along the western side of the Wodgina range, there are a number of localities where tantalum has been reported (Fig. 68). When considered together with the rich tin-bearing lodes found in the same geological environment, the area appears highly prospective for the discovery of new commercial-grade tantalum deposits. Currently, Sons of Gwalia has pegged this prospective area and will commence tantalum exploration pending land-access clearance.

Mount Francisco

Mount Francisco is located in an isolated hilly area of Archaean greenstones, about 19–25 km south-southwest of the Wodgina mine, situated on a major north-northeasterly trending regional shear that also passes through the Wodgina mining centre. The greenstones, largely composed of ultramafic rocks interspersed with smaller areas of metabasalt, metasedimentary rocks, and amphibolite schist, are probably a roof pendant suspended in the late-phase Archaean Numbana Granite (Blockley, 1980). Within this structure, a swarm of somewhat irregularly shaped pegmatites up to 600 m long and 200 m wide has intruded the greenstones.

Tantalum mineralization was discovered at Mount Francisco in 1906. Later a number of small tin, tantalum–niobium, and beryl mines were established in the area. The centre of operations appears to have been located on the southern side of Mount Francisco, a few kilometres east of Francisco Well. At this location, manganotantalite, beryl, and minor cassiterite are present in thick flat-lying pegmatite veins that extend for some distance around the contours of the hills, and are also found in adjacent gullies.

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Figure 68. View looking north to West Wodgina. Greenstone ridges on the right are prospective for tin–tantalum-rich pegmatites

In the northeastern portion of the lode, the pegmatite becomes rich in lepidolite. Steep gullies in the area were mined for eluvial manganotantalite and cassiterite, and probably yielded most of the minerals mined from Mount Francisco (Blockley, 1980).

About 7 km east of Francisco Well, abundant manganotantalite occurs in a zoned albitic quartz-cored pegmatite vein (possibly known as either 'Hooleys Columbite Lode' or alternatively the 'Numbana Mine'). The pegmatite is about 15 m in length and intrudes the Numbana Granite at this locality. Other minerals in the pegmatite include beryl, lepidolite, and microcline. In 1953–56, production from this deposit yielded about 2.6 t of $(Ta, Nb)_2O_5$ from 3.5 t of concentrate (Miles et al.,1945; Hickman, 1983).

Mount Francisco remains one of the most prospective targets for tantalum mineralization in the State. Due to land-access issues that have been awaiting resolution for over 10 years, this area is yet to be re-explored for its mineral wealth. Currently, Sons of Gwalia have an exploration licence application pending over the Mount Francisco prospect.

Yilgarn Craton

Bald Hill – Binneringie

Bald Hill mine

The Bald Hill openpit mine and primary processing plant operated by Haddington Resources Limited (formerly Haddington International Resources Limited) is located 61 km southeast of Kambalda. The property is contiguous with the Binneringie tantalum exploration area on part of its western side. At Bald Hill, pegmatites in the order of 400–600 m in length form linear swarms orientated parallel to the regional foliation of about 350°. The pegmatites have intruded Archaean metasedimentary rocks, mainly quartz–biotite schists and amphibolites, about 3–6 km east of the Binneringie granite pluton (Fig. 69).

In the area of the openpit, the tantalum-rich pegmatite is typically 1–8 m in thickness, and varies from horizontal to gently dipping to the west to a depth of about 30 m (Fig. 70). Pegmatites in the area are commonly covered by shallow colluvial material, and are often deeply weathered to kaolinite in the near-surface environment (Fig. 71). At depth, the unweathered pegmatite is composed of massive microcline, albite, and quartz, together with muscovite and minor spodumene (Fig. 72).

In early 2002, a program of 35 reverse-circulation drillholes was carried out to update knowledge of existing mine resources. Results from 259 of the 262 samples assayed yielded an average uncut grade of 0.036% Ta_2O_5 (Investor's Sharewatch, 2002).

Since that time, the company has carried out additional drilling programs on pegmatites close to the existing operations to extend the mine's known resources. In September 2002, it was announced that the Hillview pegmatite, about 100 m west of current operations, had been tested with a program of 48 drillholes. Analysis of the drilling results indicated that the pegmatite is about 450 m long, 2.5 – 3.0 m thick, dips to the west at 15–25°, and has mineralogy similar to the main Bald Hill pegmatite. The average value for 53 samples analysed was 0.039% Ta_2O_5 (Haddington International Resources Limited, 2002c).

At the same time, a program of 13 drillholes at the nearby Boreline pegmatite prospect intersected a north-striking albite–quartz–muscovite–spodumene pegmatite in 11 of the holes. This pegmatite, which ranges from 3 to 6 m in width, represents a small tantalum resource with significant intersection values varying from 0.045% Ta_2O_5 over 2.0 m to 0.050% Ta_2O_5 over 5.5 m. Two drillholes were also completed in the Cotter Bore pegmatite about 1000 m to the south. This drilling showed a pegmatite body about 6.0 m thick and yielded results up to 0.039% Ta_2O_5 over 5.0 m (Haddington International Resources Limited, 2002c).

In October 2002, as a result of these investigations the company announced an increase in the Bald Hill resource base to measured, indicated, and inferred resources of 2.0 Mt at 0.038% Ta_2O_5 (Haddington Resources Limited, 2002).

The company also has access to other prospective exploration areas in the Bald Hill area at the Bald Hill Extended and Madoonia prospects (Fig. 69), and at the Sinclair prospect about 20 km north-northwest of the Bald Hill mine. Significant pegmatites prospective for tantalum are known to occur in the Bald Hill Extended and Madoonia areas. The Sinclair prospect is situated along strike from the Bald Hill mine, in the same geological and structural environment. To date, little exploratory work has been carried out in these prospects and no other information is available. These areas are considered to be prospective for tantalum-rich pegmatite resources that will be required to supply the mine in future years.

Binneringie

The Binneringie tantalum deposit is situated about 3 km west-northwest of the Bald Hill mine. The deposit was discovered in 1981 by prospectors who subsequently carried out small-scale mining for several years at the Dawn View mine (Fig. 69). Further exploration and mining took place from 1989 to 1991, but it was not until after this period that intensive drilling campaigns were conducted. In 2001, Tantalum Australia took an interest in the project, resulting in an intensive drilling project to define resources along the eastern one-third of the property covering the old Dawn View mine.

At Binneringie, pegmatites up to several hundred metres in length form linear swarms orientated parallel to the regional foliation of about 350°. The pegmatites have intruded Archaean metasedimentary rocks (mainly mafic schist and quartzite) about 3 km east of the Binneringie granite pluton (Figs 69 and 73). A micrugranite dyke forms a low ridge along the western boundary of the exploration area. The majority of the pegmatite dykes are horizontal to gently dipping (up to 30° to the west). A few

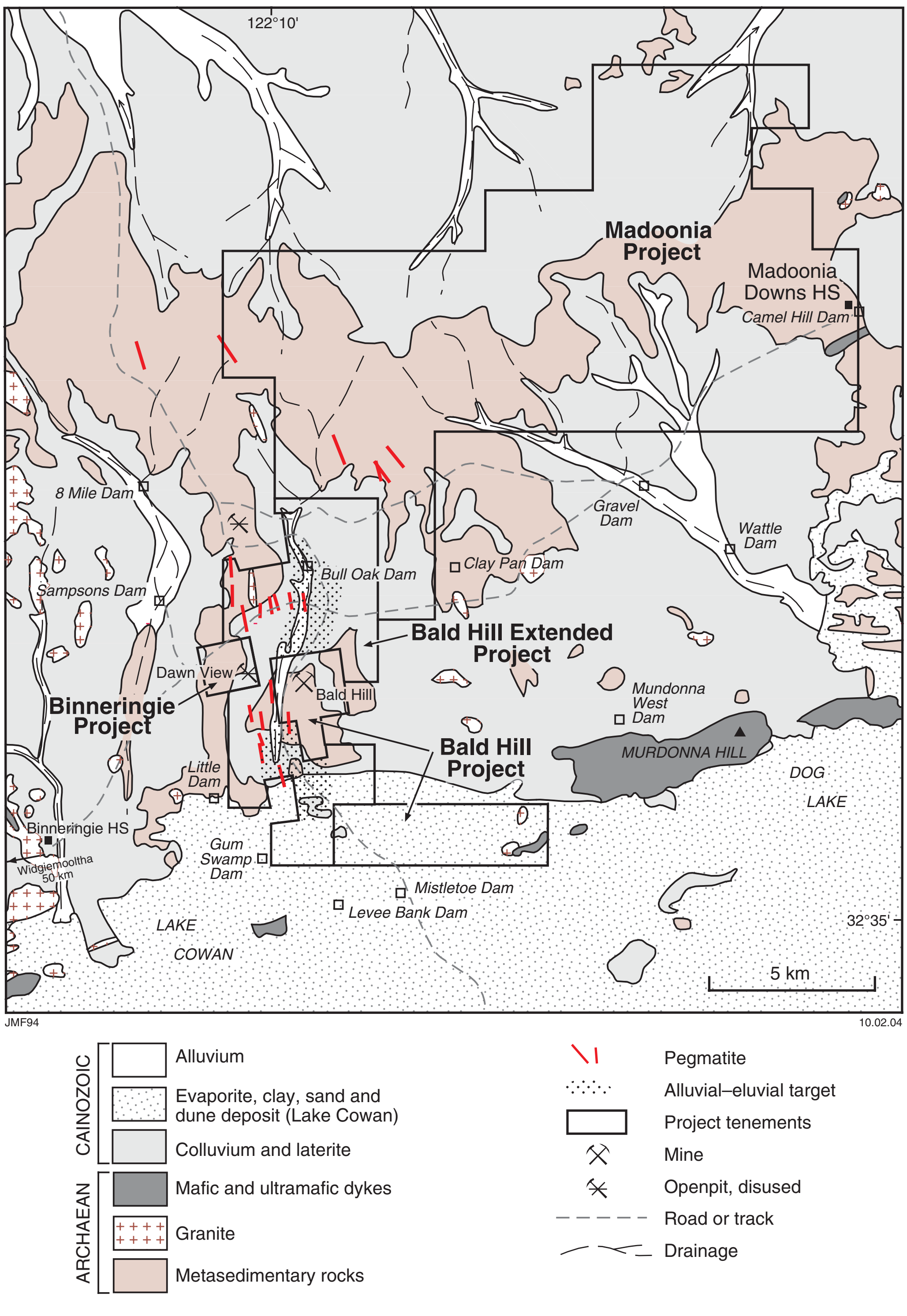

Figure 69. Geology of the area around the Bald Hill – Binneringie tantalum mining and exploration area (modified from Minerals Gazette, 2001)

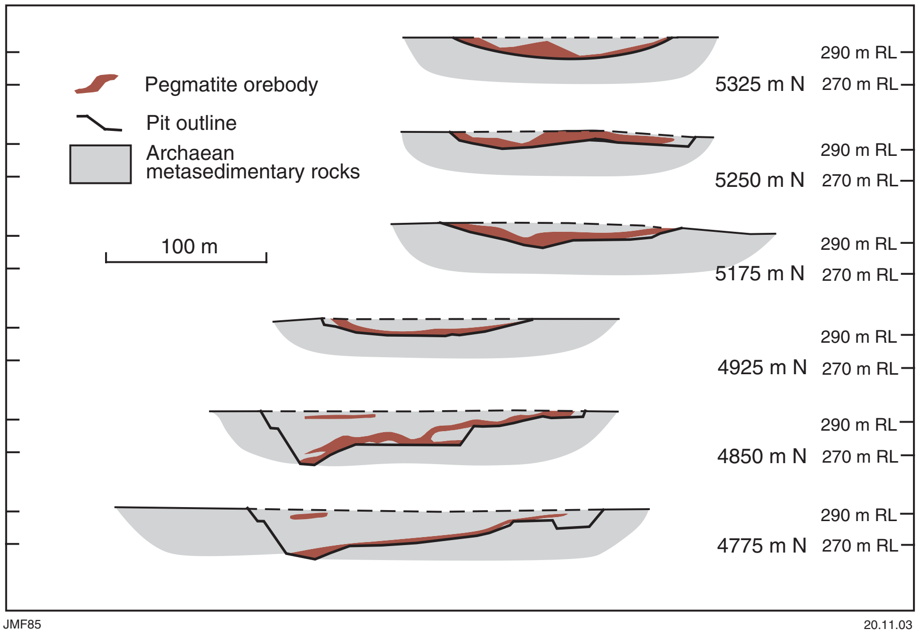

Figure 70. Cross sections through the Bald Hill openpit. Diagram shows the horizontal to gently dipping tantalum-rich pegmatite orebody extending over 550 m from north to south (modified from Haddington International Resources Limited, 2001)

Figure 71. Deeply weathered, kaolinized pegmatite overlying Archaean metasedimentary rocks in the northeastern wall of the principal openpit at the Bald Hill mine

Figure 72. Bald Hill pegmatitic tantalum ore comprising massive albite, quartz, and microcline, with lesser amounts of mica and spodumene. The visible black material is mainly manganese staining

steeply dipping dykes have been found in the area around the Dawn View openpit; however, it is considered that the near-horizontal pegmatites are more prospective for commercial tantalum mineralization. In general, the pegmatites range from 2 to 10 m in thickness and are commonly covered by shallow colluvial material.

The highly zoned Binneringie rare-metal pegmatites have been identified by Sweetapple (2000) as belonging to Cerny's complex amblygonite-type classification for rare-element pegmatites as shown in Table 8, and have yielded a rich assemblage of minerals, particularly around the old Dawn View mine. The mineralized massive albite–cleavelandite zone contains quartz, K-feldspar, and green lithium-rich muscovite. Spodumene crystals up to 1 m long have been recorded in the Dawn View pit. Tantalite mineralization is present as fine disseminations in albite–muscovite intergrowths, and also as coarse crystals 1–2 cm in length in massive albite and muscovite (Fig. 74). Whole-rock chemical analysis of the tantalite specimen in Figure 74, collected by the author, yielded Ta values of 10 491 ppm, Nb values of 5244 ppm, and Rb values of 2513 ppm respectively. Other tantalum minerals include microlite, tantite, and coarse ixiolite crystals (Fig. 75).

The latest drilling program in 2001 led to a measured resource estimate of 1.04 Mt at 0.016% Ta_2O_5 over a strike length of 600 m and to a depth of 30 m, and estimated to contain 0.17 Mt of Ta_2O_5. Indicated and inferred resources in areas adjacent to the main orebody have been estimated at 0.55 Mt at 0.014% Ta_2O_5, giving a total resource in situ of 1.52 Mt at 0.015% Ta_2O_5. Potential also exists to extend this resource southwards along strike for about 250 m. In 2003, the company intends to test this possible extension, and also a suite of pegmatites 400 m west of the main deposit at Dawn View (Tantalum Australia NL, 2002b).

Tantalum Australia has proposed that future development of the Binneringie deposit may be linked to the development of its tantalum deposit at Mount Deans near Norseman by using a common primary-concentrate plant for both deposits (Holland, 2002). It has been suggested that the company's existing milling plant at Norseman could be upgraded for the purpose.

Cattlin Creek area

Cattlin Creek

The Cattlin Creek tantalite deposit is located 2 km to the north of the town of Ravensthorpe, close to the south coast of Western Australia. The property has been explored in recent years by Haddington Resources by agreement with the owners, Sons of Gwalia.

In the mid-1900s, the Cattlin Creek pegmatite was mined intermittently for ores of tantalum and lithium (microlite and spodumene). Prior to 1958, a total of 1.1 t of tantalite and columbite was mined in the area, but since 1964 there has been no recorded mining of any mineral from the Cattlin Creek pegmatites (Thom et al., 1977). In 1963 the property was explored in detail by Western Mining Corporation. These investigations identified a spodumene resource within the pegmatite, but apparently it was assessed as being uneconomic at the time and was never mined. The deposit was again examined for tantalite

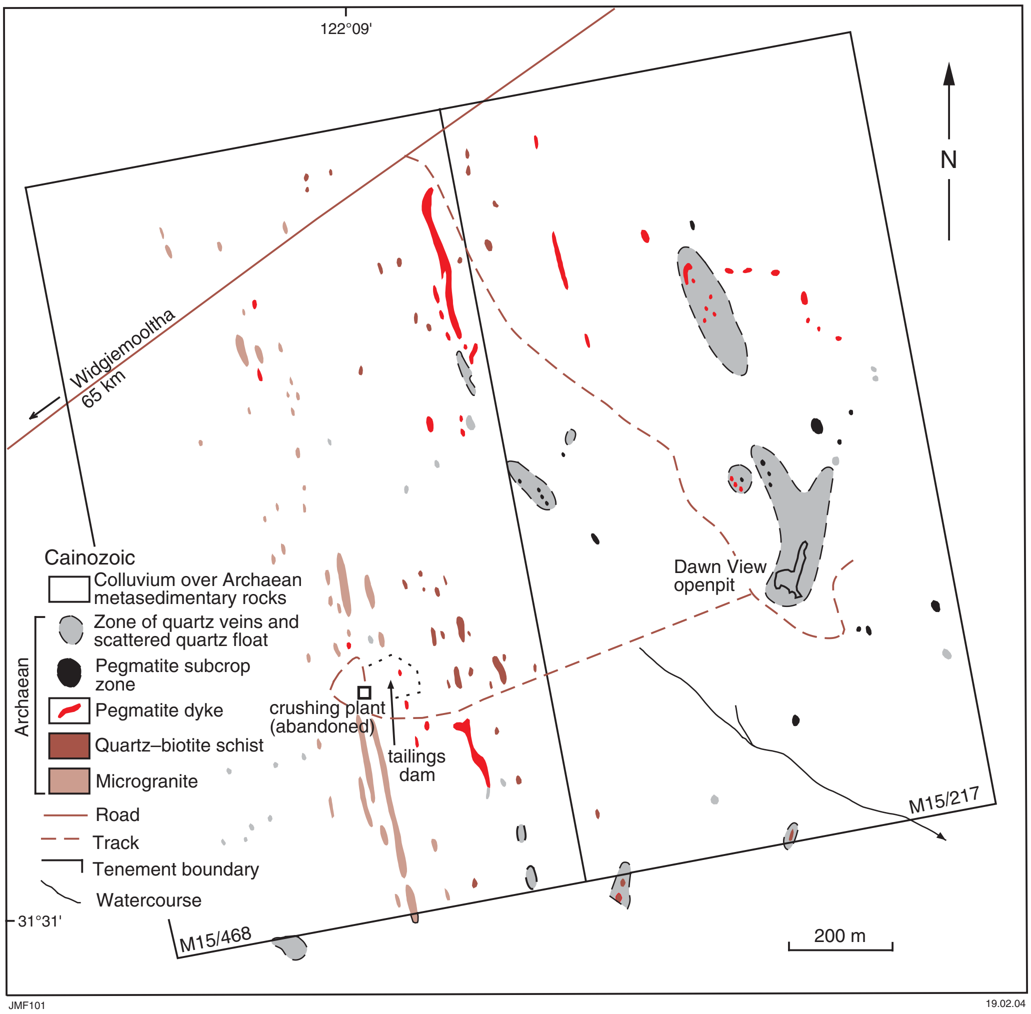

Figure 73. Outcrop geology of the Binneringie tantalum exploration area (data courtesy Tantalum Australia NL)

by Pan Continental Mining in 1988–89. Drilling revealed two tantalum-rich zones (northern and southern) separated by a quartz-gabbro dyke. However, the company did not proceed with the project due to low tantalum prices.

In 1997, Greenstone Resources carried out a resources update with a drilling program of almost 40 holes. This investigation resulted in an increased resource and proved its potential for future tantalum mining. This was further investigated by Haddington International Resources over an 18-month period starting in early 2000.

The Cattlin Creek deposit is located in a large south-plunging syncline of Archaean greenstones known as the Annabelle Volcanics, comprising metamorphosed ultramafic, mafic, and felsic volcanic rocks. Thom et al. (1977) suggested that the Ravensthorpe pegmatite swarm may be related to a late-phase Archaean granite of quartz monzonite composition that is situated about 7 km to the northeast.

The Cattlin Creek pegmatites intrude both the Ravensthorpe quartz diorite and a basaltic greenstone unit (Fig. 76). In this area, regional pegmatite zonation is apparent, with various pegmatites being recognized as

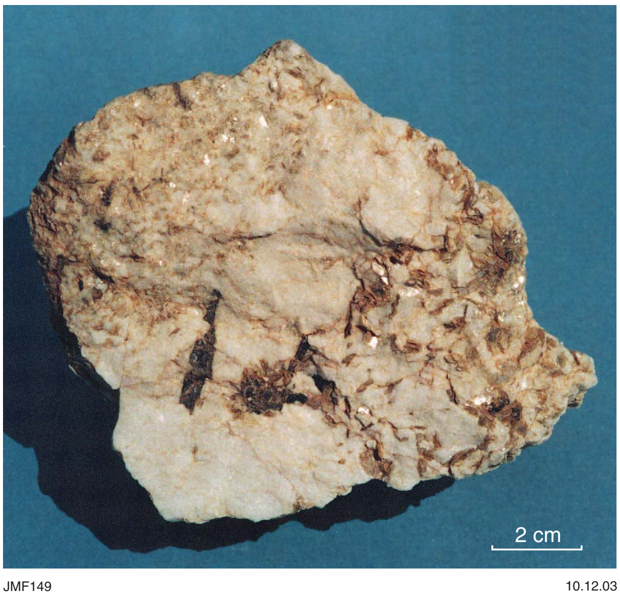

Figure 74. Coarse, black tantalite crystals and muscovite (brown with reflective plates) in massive albite. Dawn View openpit at Binneringie

belonging to the simple (albite or beryl), albite–spodumene, and complex lepidolite categories (Table 8). Tantalite mineralization (tantalite and microlite) is carried by the complex lepidolite and albite–spodumene pegmatites. The pegmatites were later cut by easterly trending Proterozoic gabbro–dolerite dykes of the Widgiemooltha suite (D. E. Cooper & Associates, 2001).

In the mineralized area of interest, a series of shallow, horizontal to gently dipping pegmatites, generally 8–12 m thick with some pods up to 20 m in thickness, extend along strike for about 240 m (Fig. 77). Within the pegmatites, mineralization is mainly confined to a high-grade zone of tantalum-rich lenses and pods surrounded by a lower grade envelope. Exploration to date has been to a depth of less than 30 m; however the deposit remains open at depth (Haddington International Resources, 2001).

In early 2002, further studies by Haddington International Resources resulted in remodelling of the Cattlin Creek orebody and downsizing of existing resources to 0.17 Mt at 0.054% Ta_2O_5. It was estimated that this resource downgrade would reduce the deposit's mine life to about one year. These results have prompted the company to put mine development at Cattlin Creek on hold pending further exploration to find additional resources in the area (Haddington International Resources Limited, 2002a).

Figure 75. Ixiolite crystal from the Dawn View openpit at Binneringie

North Ravensthorpe

In 2001, Galaxy Resources applied for a number of mining leases and an exploration licence surrounding Haddington International Resources' mining lease at Cattlin Creek. To date, the area of principal interest has been the North Ravensthorpe property, about 3 km north of the Ravensthorpe township and contiguous with the northern boundary of the Cattlin Creek mining lease.

Some of the pegmatites investigated at North Raventhorpe are an extension of the swarm already described at Cattlin Creek, which is hosted by metamorphosed ultramafic, mafic, and felsic rocks of the Archaean Annabelle Volcanics. Between 1 and 2 km to the east, another swarm of north-trending pegmatites has intruded both the Annabelle Volcanics and the adjoining calc-alkaline Manyutup Tonalite, also of Archaean age. The north-trending boundary between these units is considered significant since it appears that the bulk of the mineralized pegmatites are located within 2 km of this boundary (Fig. 78).

The North Ravensthorpe pegmatites so far investigated are gently dipping, up to 21 m in thickness, and thin to

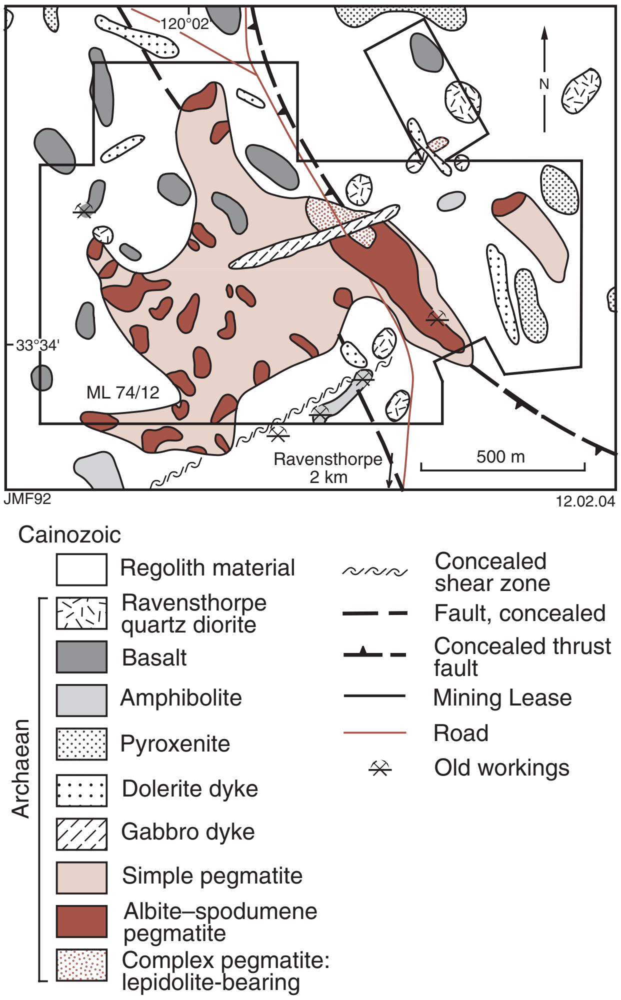

Figure 76. Geology of the Cattlin Creek exploration area (data courtesy of Haddington International Resources Limited)

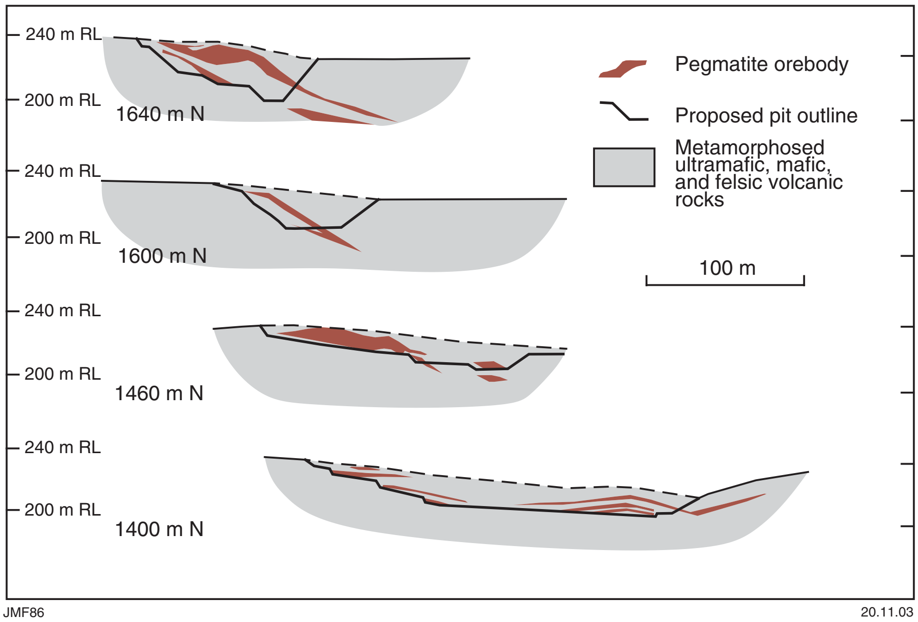

Figure 77. Cross sections through the Cattlin Creek deposit. Diagram shows the structure of the tantalum-rich orebody extending over 240 m from north to south (modified from Haddington International Resources Limited, 2001)

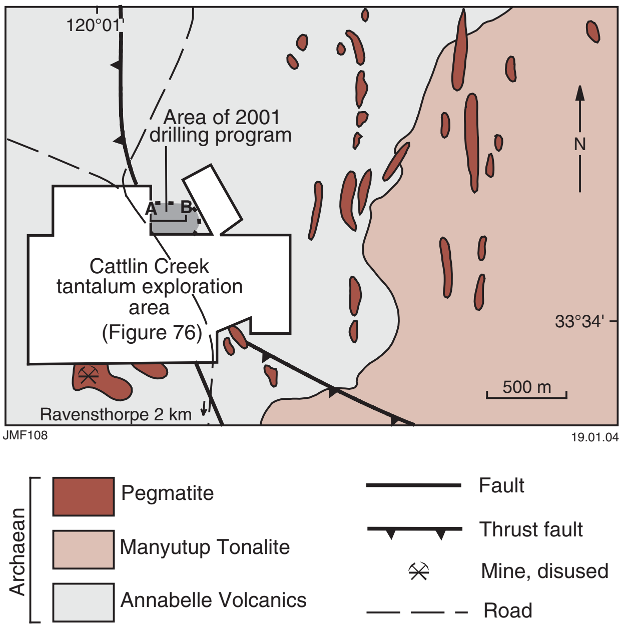

Figure 78. Geology of the North Ravensthorpe exploration area. Diagram shows a swarm of potentially mineralized pegmatites to the northeast of Ravensthorpe (modified from Galaxy Resources Limited, 2002)

the north and east. An overburden of quartz gabbro and intermediate to mafic metavolcanics varies from 25 m in the southwest to 60 m in the northeast. In this area, columbite–tantalite and microlite mineralization is found in irregular pods and in bands of lepidolite with pink and green tourmaline and exhibiting secondary lithium alteration within a zone of albite, quartz, spodumene, muscovite, and black tourmaline.

During 2001, Galaxy Resources drilled 116 reverse-circulation and six diamond drillholes in the North Ravensthorpe area adjacent to the Cattlin Creek mining lease. A cross section showing significant drillhole Ta_2O_5 intercepts in pegmatite is shown in Figure 79. As a result of this exploration program, the company announced a measured and indicated resource of 0.85 Mt at 0.039% Ta_2O_5. Also announced was an inferred resource of 0.21 Mt at 0.035% Ta_2O_5, with the deposit still being open to the north and northeast (Galaxy Resources Limited, 2002).

Cobalark

The Cobalark prospect is located about 60 km east-southeast of Meekatharra in the eastern Murchison district. The area was briefly prospected by Quantum Resources in 2001. The area of exploration comprises scattered outcrops of late-stage Archaean biotite-adamellite granitoids intruded in places by muscovite-rich pegmatites. In many places these rocks have been deeply weathered to kaolin and ferruginous laterite. Grab samples analysed from surface laterite samples returned 0.017% and 0.007% Ta_2O_5, 0.172% Nb_2O_5, and 0.024% SnO_2. To date, no further exploration work has been carried out (Quantum Resources Limited, 2001).

Cocanarup

Mineralized tantalum prospects occur in areas of extensive pegmatite swarms 20–28 km southwest of Ravensthorpe. In 2001, the area was partially explored by Galaxy

Resources. As is the case with the Cattlin Creek and North Ravensthorpe tantalum deposits to the northeast, the Cocanarup pegmatites are also hosted by the Archaean Annabelle Volcanics (mainly metamorphosed felsic volcanic rocks). In the Cocanarup area, the metavolcanic rocks are steeply dipping and host flat-lying pegmatite bodies that may be up to 20 m thick and extend for up to 1 km.

Tantalum mineralization has been observed in the pegmatites as flat, stubby crystals and fragments, together with tourmaline, in vuggy pockets several centimetres in diameter that are distributed irregularly within the pegmatite. Lithium alteration is also evident and associated minerals include lepidolite, zinnwaldite, and amblygonite.

In the northern part of the exploration area is located an old tantalite quarry from which 0.75 t of tantalite and manganotantalite is understood to have been recovered by hand-sorting of ore in past years (Fig. 80). Specimens collected from this quarry assayed 21.6% Ta_2O_5 and 56.8% Nb_2O_5. A channel sample collected from a pegmatite about 3.5 km to the south-southeast yielded 0.025% Ta_2O_5 (Galaxy Resources Limited, 2002).

Galaxy Resources considered the Cocanarup area to be highly prospective for tantalite deposits and at the time proposed that a comprehensive drilling and channel-sampling program should be carried out. Unfortunately, due to a lack of finance this program did not eventuate.

Dalgaranga

Dalgaranga is located about 80 km northwest of Mount Magnet in the Murchison region of the State. In the Dalgaranga area, there are numerous rare-metal pegmatites that have been worked for beryl and tantalite for about 60 years.

The Dalgaranga tantalum deposits are located in Archaean greenstones close to several late-stage Archaean granodiorite intrusions situated near of the intersection of the southwest extension of the Big Bell shear zone and the north-trending Warda Warra shear structure (Fig. 81).

Currently, Tantalum Australia mines tantalum minerals from the openpit at Dalgaranga for processing at its on-site primary concentration plant (see Chapter 6). The company has carried out investigations of other local pegmatites including the nearby Niobe openpit (formerly known as Mount Farmer; Fig. 82) and the Breakaway deposit, both about 7 km to the east, and also the Tantalus prospect about 27 km to the north-northwest. The company also has access to a number of other pegmatites in the Dalgaranga–Niobe area in the mafic–ultramafic greenstones along the Warra Warda shear structure, south of the abandoned Western Queen gold mine (Tantalum Australia NL, 2002b).

Dalgaranga mine

At Dalgaranga, a shallowly dipping pegmatite hosted by mainly Archaean metasedimentary rocks is orientated along the northeasterly strike of the southwest extension of the Big Bell regional shear structure. The pegmatite comprises a quartz core surrounded by a zone of massive albite–cleavelandite characterized by irregular masses of black botryoidal muscovite (Figs 83 and 84). Mineralization consists of tantalite, beryl, and significant quantities of microlite (Fig. 85). Chemical analysis of tantalite and microlite mineralization from the deposit indicated 59.11 and 58.15% Ta, and 5.93 and 1.63% Nb respectively.

Early in 2002, the Dalgaranga openpit was thought to be almost exhausted; however, recent exploration indicated the possibility of a downdip extension of the pegmatite up to 5–6 m thick and 250 m in length. One drillhole

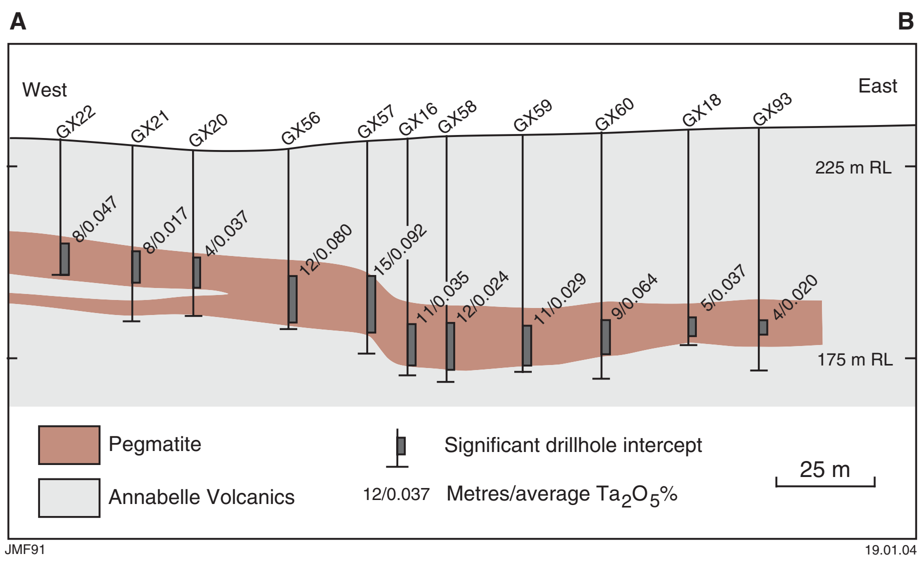

Figure 79. East–west cross section through a tantalum-rich pegmatite at North Ravensthorpe (modified from Galaxy Resources Limited, 2002)

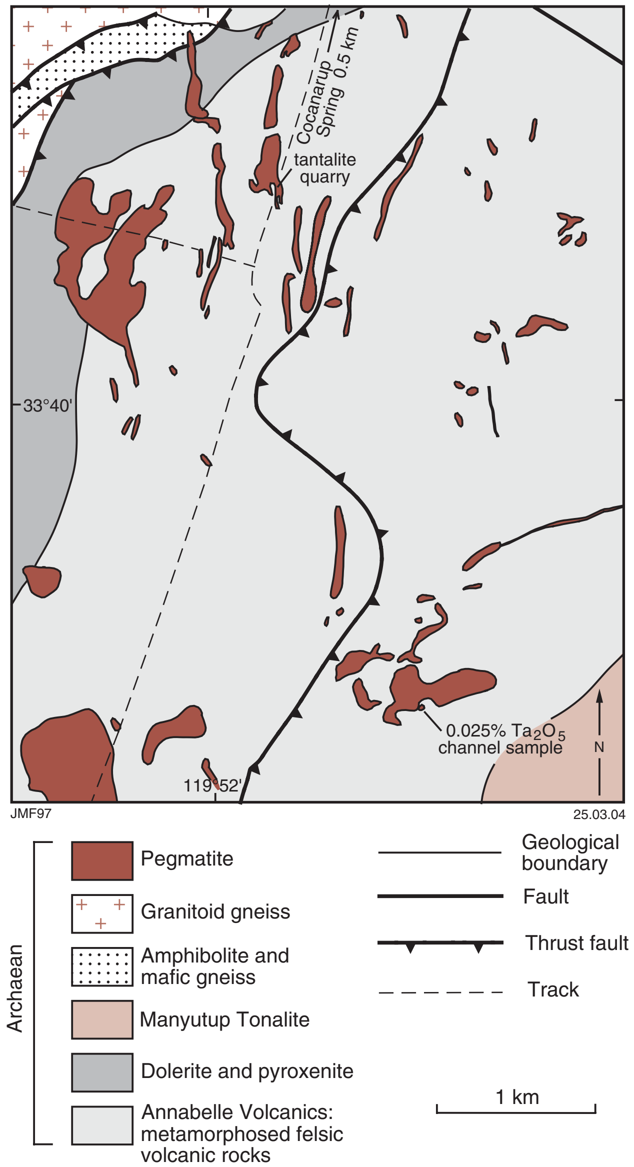

Figure 80. Tantalum exploration area at Cocanarup (modified from Galaxy Resources Limited, 2002)

yielded a pegmatite intercept of 6 m at 0.028% Ta_2O_5 and investigations are continuing (Tantalum Australia NL, 2002a).

Niobe

Located about 7 km east of Dalgaranga, the Niobe deposit is situated on a high-grade mineralized pod within a pegmatite that forms part of a swarm of northeasterly trending zoned pegmatites orientated parallel to the Big Bell shear zone (Fig. 81). These pegmatites exhibit moderate dips of up to 40º to the northwest and have preferentially intruded a unit of Archaean metagabbro. It has been noted that zoned albite–zinnwaldite-bearing pegmatites in this area exhibiting this preferred orientation tend to return high Ta_2O_5 grades.

In the Niobe openpit, the sharp, straight contact between the hangingwall of the pegmatite and the overlying metagabbro (possibly a sill) is clearly visible (Fig. 86). The pegmatite, which is up to 30 m thick in the area of the openpit, is split into an upper albitic low-grade zone (<0.01% Ta_2O_5) above a barren quartz core, and a lower albitic high-grade zone with an average grade of 0.03% Ta_2O_5 (Fig. 87). Both upper and lower pegmatites show distinct albite–muscovite–zinnwaldite zonation and contain accessory minerals such as beryl, tourmaline, fluorite, garnet, and lepidolite. Also present are unusual rosettes of emerald-green muscovite (Fig. 88), and masses of black botryoidal muscovite (also seen at Dalgaranga).

Niobe was first mined in 1995. At that time, the deposit was known as Mount Farmer and the mining campaign produced almost 19 000 t of ore that yielded 38.9 t at 0.05% Ta_2O_5. Since that time, several drilling programs have targeted the downdip resource below the Niobe pit and the adjacent Niobe East prospect along strike. These campaigns have provided sufficient information to estimate a measured resource of 57 550 t at 0.024% Ta_2O_5. The deposit also has surrounding dumps of low-grade ore estimated to contain a further 36 000 t at 0.031% Ta_2O_5. (Tantalum Australia NL, 2001, 2002b).

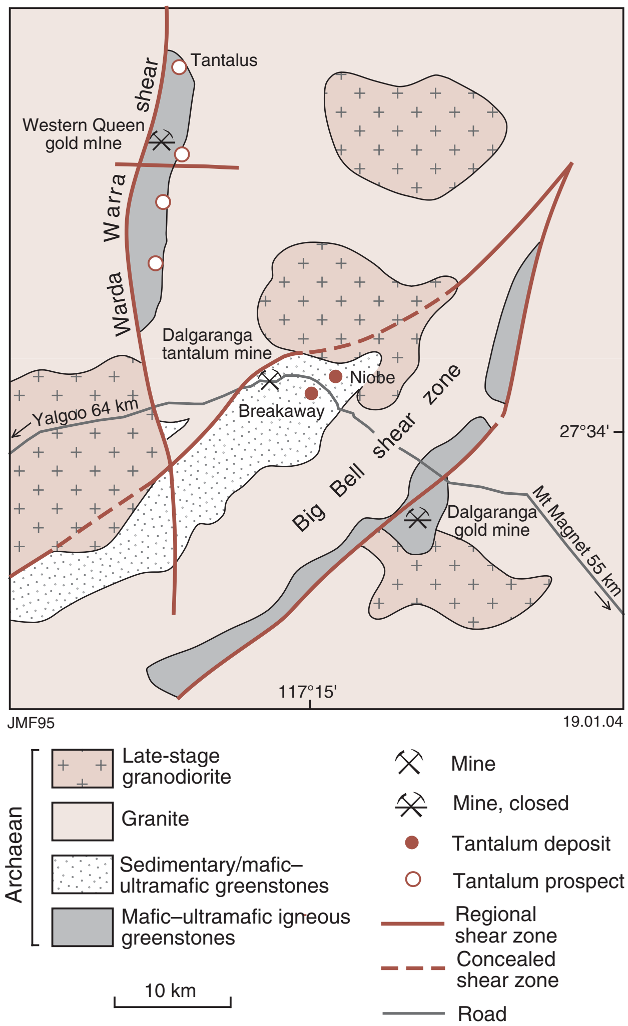

Figure 81. Geology of the area around Dalgaranga (modified from Tantalum Australia NL, 2002b)

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Figure 82. The Niobe openpit (formerly known as Mount Farmer) at Dalgaranga (looking northeast)

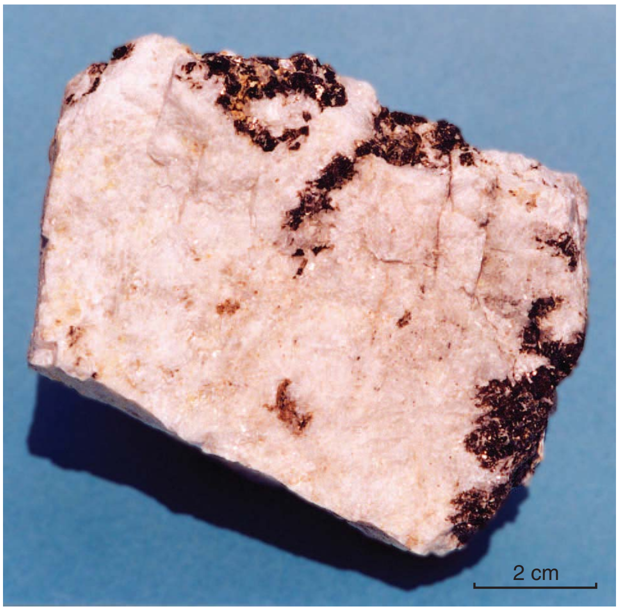

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Figure 83. Massive cleavelandite, and muscovite hosting tantalum mineralization, Dalgaranga openpit

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Figure 84. Sample of black, botryoidal muscovite mass, Dalgaranga openpit

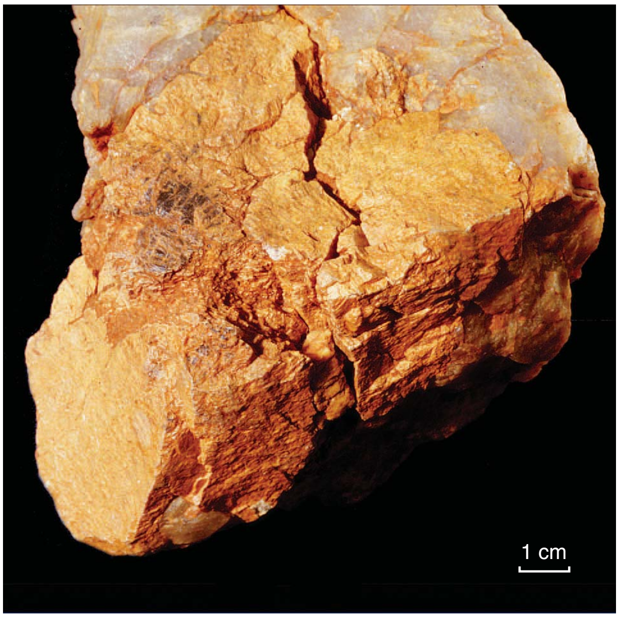

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Figure 85. Microlite, a significant component of the tantalum mineralization at Dalgaranga (Simpson Collection, Western Australian Museum)

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Figure 86. Sharp, straight contact between pegmatite and the overlying host metagabbro at the Niobe openpit (looking north)

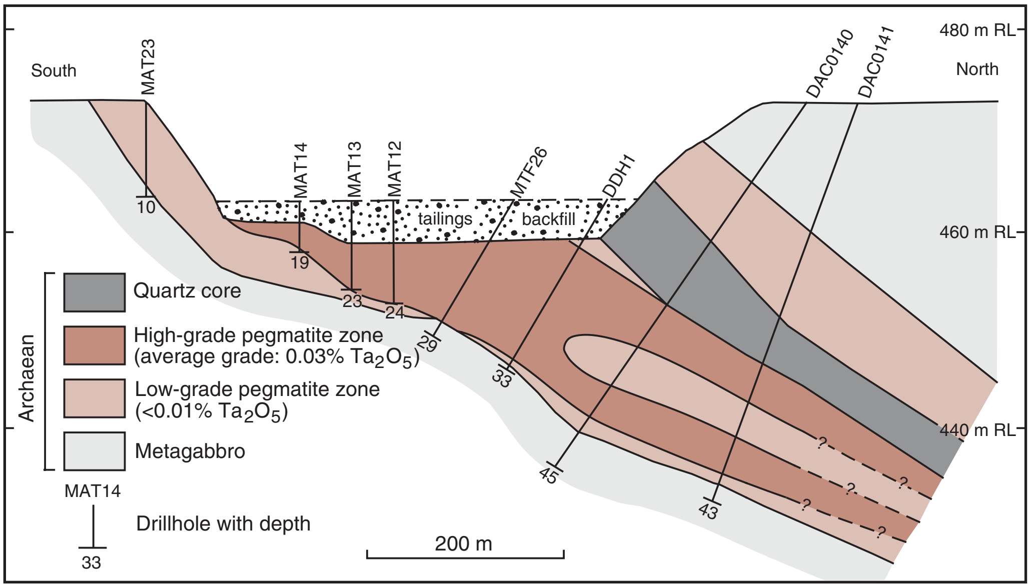

Figure 87. North–south cross section through the Niobe openpit (data courtesy Tantalum Australia NL)

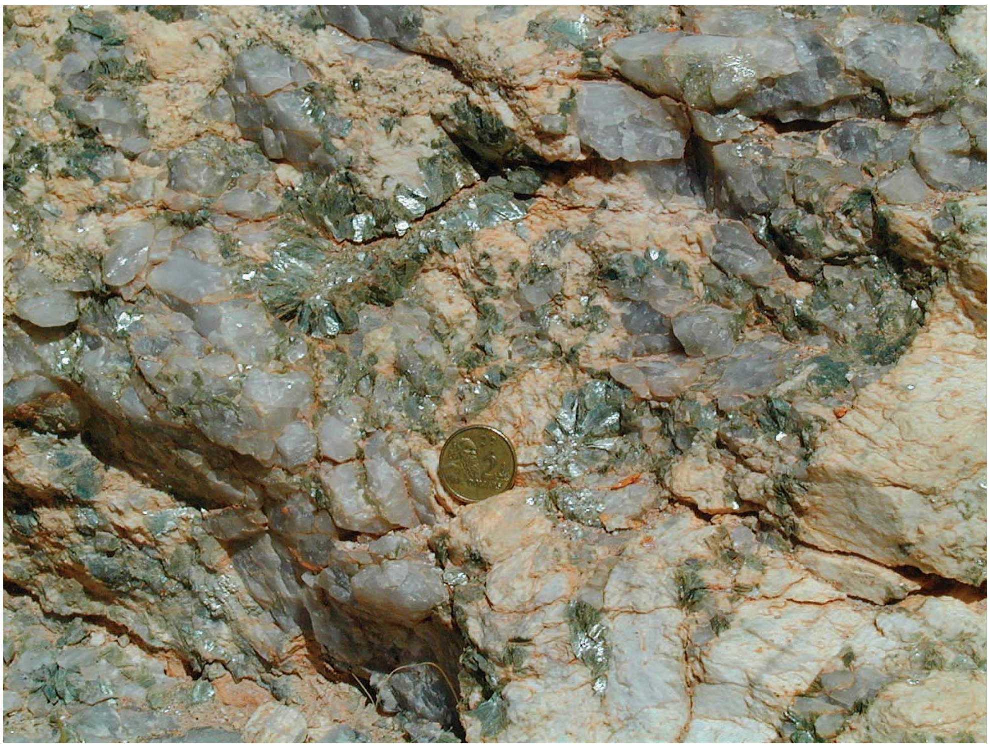

Figure 88. Rosettes of emerald-green muscovite mica, Niobe openpit

Breakaway

The Breakaway deposit is located about 1 km to the southwest of the Niobe openpit. In 2002, reconnaissance drilling intersected a highly weathered pegmatite to a depth of 20 m. Drill results showed the pegmatite to be generally thicker than 10 m and gently dipping about 15° east. An estimate of the higher grade resources over a strike length of 80 m was 0.13 Mt at an average grade of greater than 0.014% Ta_2O_5 (Tantalum Australia NL, 2002b).

Tantalus

The Tantalus pegmatite prospect, located about 27 km north-northwest of Dalgaranga, is contained within mafic–ultramafic greenstones adjacent to the north-trending Warda Warra shear structure (Fig. 81). The low-angle easterly dipping pegmatite is a linear body about 300 m in strike length and ranging from about 10 to 25 m in thickness. It contains a large low-grade tantalum resource measuring greater than 0.01% Ta_2O_5 at its northeastern end. Bulk samples from the prospect are currently being assessed for overall tantalite concentration levels.

The pegmatite is exposed in a small openpit on-site, in which beryl mining originally took place. This pegmatite is composed mainly of quartz and massive cleavelandite that has been commonly replaced by zones of sugary albite (Fig. 89). The cleavelandite also commonly contains masses of hard, interlocking, silvery, cone-shaped crystalline structures approximately 10–15 cm in length. X-ray diffraction analysis has shown the mineral to be an unusual form of muscovite mica (Fig. 90).

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Figure 90. Hard, interlocking, cone-shaped structures of silver-coloured muscovite (10–15 cm in length) within massive cleavelandite, Tantalus prospect

Greenbushes mine

Greenbushes is situated about 300 km south of Perth and 80 km southeast of the port of Bunbury, which is in the southwest of the State.

Tin was first discovered in the Greenbushes area in 1886, followed by stibiotantalite in 1893 and in 1900 tantalite was found in alluvial ore. In the early 1960s, dredge mining of placer deposits began in earnest for tin and tantalum. This continued until the early 1970s when attention turned to openpit mining of weathered pegmatites contained in a kaolinized regolith horizon, up to 50 m thick, overlying the primary deposit.

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Figure 89. Replacement of cleavelandite (right) by sugary albite (left) at the Tantalus prospect

The substantial increase in demand and associated price rises for tantalum in the early 1980s saw an increase in production from the weathered pegmatites, as well as an acceleration of a deep-drilling program to delineate the hard-rock tantalum orebody beneath the regolith cover. In 1990, with hard-rock openpit mining underway, the operations became part of Gwalia Consolidated. Today, the project is owned and operated by Sons of Gwalia, and the Greenbushes orebody is the world's largest hard-rock tantalum resource and mining operation, producing up to 560 t Ta_2O_5 per annum from the Cornwall openpit.

In 2002, Sons of Gwalia announced that the Greenbushes deposit has total reserves and resources estimated at 223.7 Mt at 0.22% Ta_2O_5 comprising proven and probable reserves of 88.6 Mt at 0.022% Ta_2O_5 estimated to yield almost 20 000 t Ta_2O_5 , and measured, indicated, and inferred resources of 135.1 Mt at 0.022% Ta_2O_5 estimated to yield over 29 000 t Ta_2O_5 (Sons of Gwalia Ltd, 2002a). The deposit contains substantial resources of tin that are also recovered in the mining and processing operations.

The following description is a summary of the principal features of the hard-rock Greenbushes pegmatite and its tantalum–tin mineralization. A full description of this orebody has been given in Partington et al. (1995) and Hatcher and Clynick (1990).

The Greenbushes pegmatite comprises a swarm of mostly very large north-trending pegmatites that were intruded into gneiss, amphibolite, granofels, ultramafic schist, and banded iron-formation situated in the Archaean Balingup Metamorphic Belt. The age of emplacement of the Greenbushes pegmatite is estimated at 2527 ± 2 Ma (Partington et al., 1995); however, its origin remains uncertain. Previously, it had been proposed that the only large local granitoid, the Logue Brook Granite (a pluton of the Wheatbelt batholith), was the pegmatite's parent granite (Blockley, 1980). This granite was later dated at 2612 ± 5 Ma, approximately 85 million years prior to the intrusion of the pegmatite. Furthermore, the mineralogical and geochemical characteristics of local granite bodies show little resemblance to those of the specialized granitoids and are therefore unlikely to be genetically related to the pegmatite (Partington et al., 1995).

The pegmatite swarm was intruded close to, and aligned with, the north to north-northeasterly trending Donnybrook–Bridgetown shear zone, a regional lineament about 150 km in length. At Greenbushes, the pegmatite swarm takes the form of linear dykes with a strike length of about 7 km and a width of about 1 km. Within this swarm, the largest pegmatite is about 3.3 km in length and varies in width from 40 to 250 m. It has been drilled to a depth of 500 m. In general, the pegmatites dip westerly at about 40–50°, although there are substantial local variations in attitude. A section of these pegmatites around the Greenbushes mine site is illustrated in Figure 91. Other related pegmatites situated on the same shear zone are located at Ferndale and Mullalyup, 10 and 15 km to the north respectively.

Bettenay et al. (1988) suggested that the deformation and metamorphic events within the Donnybrook–Bridgetown shear zone were synchronous with the

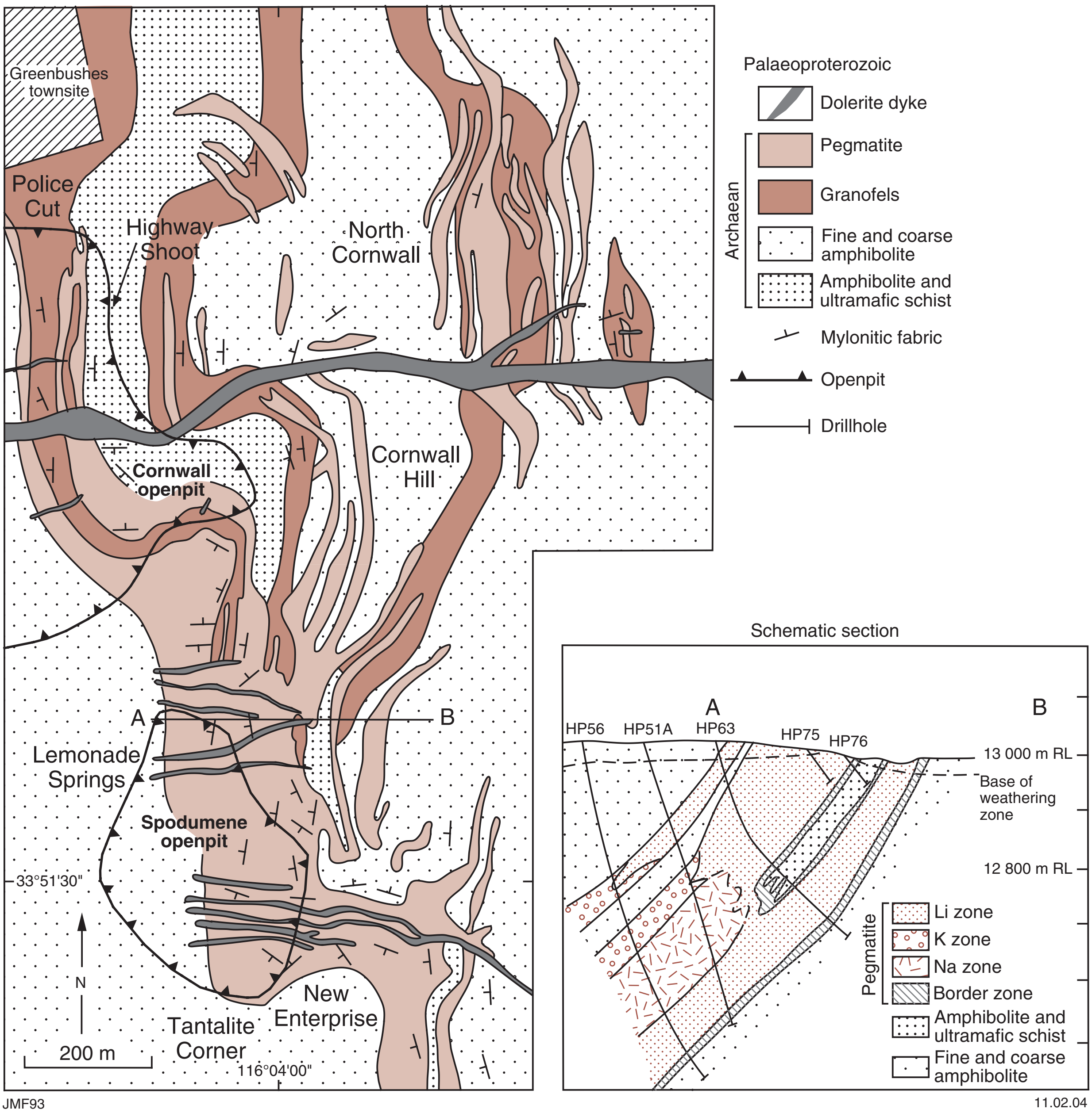

Figure 91. Geological map of the Greenbushes pegmatite, with schematic cross section showing the zonation pattern (modified from Partington et al., 1995)

Table 31. Zonation pattern in the Greenbushes pegmatite

Zone	*Mineral assemblage* Major	*Mineral assemblage* Minor	*Ore mineralogy*
Border zone (contact zone)	Albite, quartz	Muscovite, tourmaline, biotite, garnet, zircon, scapolite, calcite, holmquisite	Tantalite and other Ta–Nb minerals, cassiterite
K zone (K-feldspar zone)	Microcline, quartz, perthite	Muscovite, spodumene, tourmaline, beryl, apatite	Ce- and Rb-enrichment
Na zone (albite zone)	Albite, quartz	Muscovite, tourmaline, apatite, microcline, zircon, spodumene	Tantalite, cassiterite, stibiotantalite, microlite, tapiolite, wodginite, holtite
Li zone (spodumene zone)	Spodumene, quartz	Muscovite, apatite, tourmaline, perthite, albite, beryl	Spodumene

SOURCES: Hatcher and Clynick (1990); Partington et al. (1995)

emplacement and crystallization of the Greenbushes pegmatite, and that these events may have been responsible for the location, morphology, and internal structure of the pegmatite swarm.

At Greenbushes, the tin–tantalum–spodumene pegmatites are made up of four layered units without a classic concentric zonation pattern, and belong to the complex spodumene subtype of rare-element pegmatites shown in Table 8 (Sweetapple, 2000). The atypical zonation pattern seen at Greenbushes includes a border or contact zone, a K-feldspar zone, a Na (or albite) zone containing the main tantalum mineralization, and a Li (or spodumene) zone that is the main source of lithium mineralization. The spatial relationship of these zones is shown in Figure 91 and details of the zonation patterns are given in Table 31.

The high degree of fractionation in the layered pegmatite units has enabled the formation of discrete lodes enriched in tantalum–tin and lithium-rich spodumene. This can be seen in the block diagram of the Greenbushes deposit (Fig. 92) in which the major tantalum–tin mineralization that occurs within the Cornwall and Hanging Wall lodes is mined from the Cornwall openpit. The lithium-rich lode is accessed from the Lithium pit, and the Central lode to the south has discrete areas of both types of mineralization and is currently set aside as a future resource.

Currently, tantalum–tin mining operations are carried out in the huge Cornwall openpit that is well over 200 m deep. The tantalum–tin mineralization is located in three thick, massive albite–quartz pegmatite veins known as Pegmatites A, B, and C that belong to the Na (albite) zone. These veins, which are hosted by amphibolite and granofels greenstones, dip steeply westward at 30–75° (Figs 93 and 94). The pegmatites are composed mainly of massive albite (occasionally as cleavelandite) and quartz,

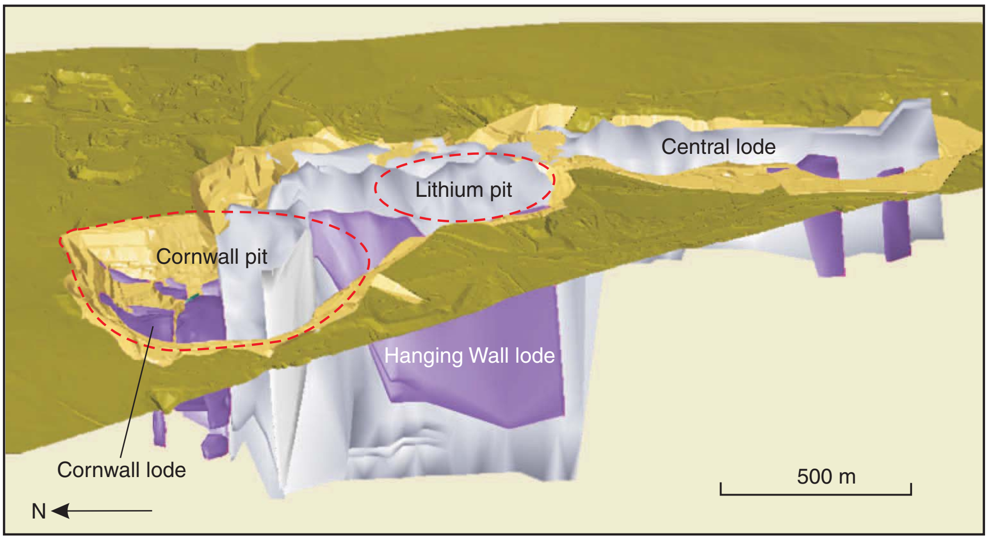

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Figure 92. Block diagram showing distribution of the tantalum- and lithium-rich pegmatite lodes at Greenbushes (modified from Sons of Gwalia Ltd, 2002b)

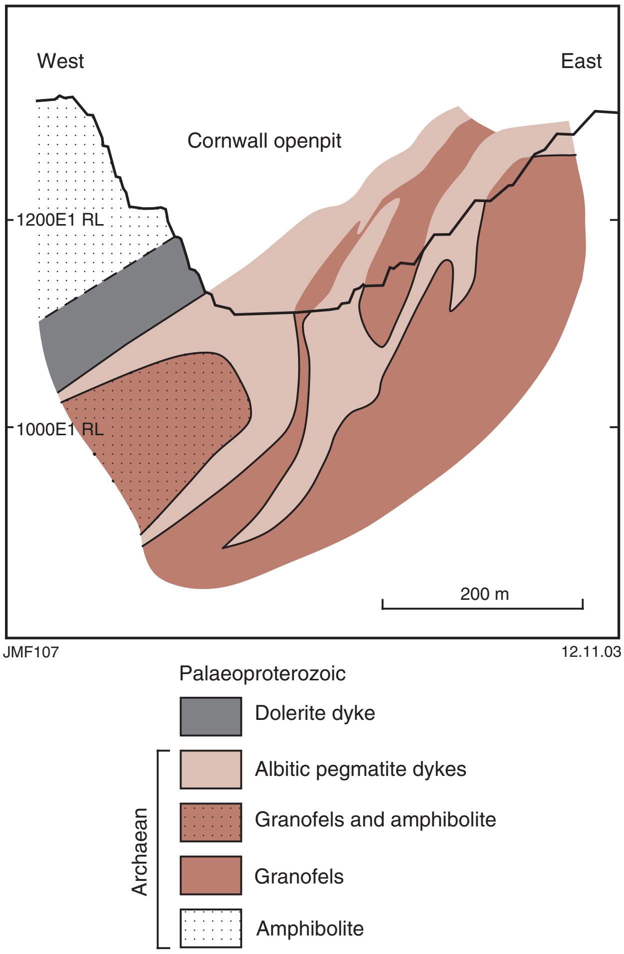

Figure 93. East–west cross section through the Cornwall openpit at Greenbushes. Diagram shows the relationship of the tantalum–tin-rich albitic pegmatites with the granofels and amphibolite host rocks (data courtesy Sons of Gwalia Ltd)

commonly appearing as a fine-grained, heterogeneous, crystalline admixture together with muscovite, tourmaline, apatite, and spodumene (Fig. 95). Other pegmatite minerals include microcline and zircon. In general, the grain size of most minerals is in the range 0.1 – 0.5 mm; however, individual mineral grains, particularly tourmaline, may exceed 10 mm in diameter (Hatcher and Clynick, 1990).

Ore minerals from the Na (albite) zone are for the most part fine to very fine grained. Tantalite is the most common tantalum–niobium mineral, usually in the form of rectangular prisms 0.01 – 0.5 mm in diameter. Cassiterite, the source of the deposit's tin, is present as black to reddish-brown crystals, commonly less than 1.0 mm in diameter, but can reach 10 mm on occasions. Other tantalum minerals include stibiotantalite, microlite, tapiolite, wodginite, and minor holtite. Holtite is a complex borosilicate mineral containing tantalum, niobium, antimony, and arsenic. It is found in complex granitic rare-metal pegmatites. At Greenbushes, holtite is found as coatings on stibiotantalite, and as a minor replacement for tantalite (Gaines et al., 1997).

Studies conducted by Wilde (1990) on ore samples from the Na (albite) zone led to a number of observations in relation to tantalite mineralization within the tantalum–tin orebody:

- Tantalite occurs both as independent grains and as inclusions in other minerals, commonly as small rods and prisms;
- Tantalite tends to occur in close proximity to the boundaries of many minerals, especially albite–albite and quartz–albite boundaries, often in association with cassiterite, and at apatite–tourmaline boundaries as shown in Figure 96;
- Tantalite occurs as inclusions in at least six mineral species, particularly in cassiterite where it is found as minute exolved blebs (<65 µm in diameter) and in tourmaline as small rods (Fig. 97). Tantalite grains are also found in muscovite, spodumene, albite, and quartz crystals; and
- Tantalite forms a wide range of mineralogical associations with many minerals, especially albite, quartz, apatite, spodumene, tourmaline, and muscovite.

Wilde (1990) stated that the presence of tantalite grains within other minerals is significant. It appears that these inclusions were formed as a result of extensive modification of the original distribution of ore minerals by recrystallization and the new grain growth that took place during post-magmatic and metamorphic processes. This would tend to explain the large number of tantalite mineralogical associations present, and the development of tantalum at a variety of grain boundaries.

Londonderry

Tantalite Hill

Located about 21 km south-southwest of Coolgardie in the Eastern Goldfields, the Londonderry pegmatites were discovered in 1900 by H. Fraser. It was not until 1914 that the first pits were sunk into lenses of lepidolite, but these proved to be uneconomic. Between 1939 and 1979, Australian Glass Manufacturers mined potash feldspar from the pegmatites in the Londonderry openpit. The company also mined small quantities of tantalite, columbite, and beryl as byproducts from this pit and also from the Lepidolite Hill openpit (Fig. 98). In 1938, British Tantalite produced small quantities of tantalite and columbite from the Tantalite Hill openpit (Fetherston et al., 1999). Total recorded production of tantalite and columbite from the pegmatites at Londonderry is 4.0 t.

The three Londonderry pegmatites have intruded a south-trending suite of metamorphosed Archaean greenstones comprising metagabbro and other metamorphosed mafic intrusive rocks, komatiite flows, and high-magnesian basalt. The pegmatites appear to have a relationship with a coarse-grained biotite monzogranite that forms small intrusions and sheeted complexes together with pegmatite and aplite within the greenstone sequence (Hunter, 1993).

The Londonderry, Lepidolite Hill, and Tantalite Hill pegmatites were examined by London (1986) who

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Figure 94. Massive, steeply dipping tantalum–tin-rich pegmatites intruding amphibolite and granofels in the south wall of the Cornwall openpit

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Figure 95. High-grade tantalum ore from Pegmatite C, Cornwall openpit. Visible minerals: albite (white), quartz (pale grey), tourmaline (black), muscovite (yellow with reflective plates), and apatite (grey-green)

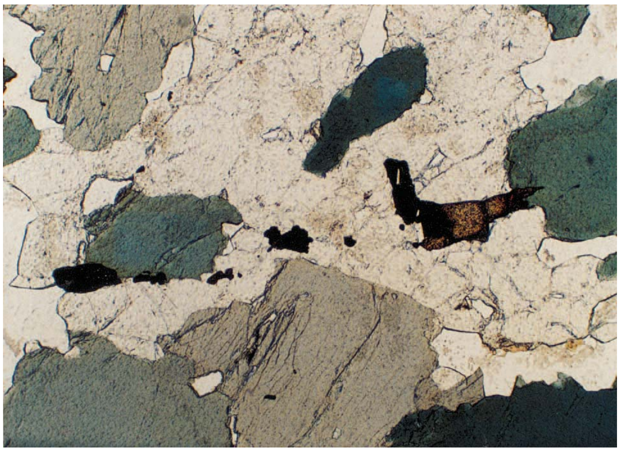

Figure 96. Trail of black cassiterite and tantalite grains (0.15 – 0.5 mm long) enclosed in apatite. The tantalite grains form contacts with cassiterite, and also along the margins of (and within) green tourmaline crystals (plane polars × 25; after Wilde, 1990)

proposed that the Lepidolite Hill and Tantalite Hill pegmatites were much more fractionated than the larger Londonderry pegmatite, due to the abundance of incompatible elements such as lithium, niobium, and tantalum. Later, Cross (1993) identified zonation patterns for these bodies. The zonation pattern for Tantalite Hill is shown in Table 32. The highly fractionated Tantalite Hill rare-metal pegmatites have been identified by Sweetapple (2000) as belonging to Cerny's complex petalite-type classification for rare-element pegmatites as shown in Table 8.

The Tantalite Hill pegmatite consists of two main flat-lying pegmatite bodies — a southern sheet-like body and a northern keel-shaped body. The southern body has a variable thickness averaging about 5 m, and a length of about 230 m trending east-northeast, with an outcrop width of about 120 m. The northern body is 25 m thick, 130 m long, and has an outcrop width of 50 m (Haynes, 1966).

In late 2001, the area around Tantalite Hill was drilled by Rusina Mining with a program of four vertical reverse-circulation drillholes to test zonation patterns for tantalum, niobium, and lithium minerals. Results of the drilling confirmed pegmatite thickness variations of up to 15 m, and assays of 0.008% Ta_2O_5 and 0.045% Li_2O over 4 m were obtained. A future target area containing stacked pegmatite sheets and measuring 1.5 × 1.0 km was identified for further drilling.

In mid-2002, Rusina Mining withdrew from the Londonderry tantalum exploration project in favour of the joint venture partner Plato Mining.

Mount Deans

The Mount Deans exploration area is located in the Dundas Hills between 8 and 13 km south of Norseman in the Eastern Goldfields. In this area, a swarm of numerous north-trending pegmatite veins has intruded Archaean metabasalts of the Woolyeener Formation. The swarm covers an area of about 5 km in a north–south direction and 2 km in an east–west direction (Fig. 99). The pegmatites are highly fractionated with respect to elements such as lithium, rubidium, and caesium, and are thought to have emanated from the late-phase Archaean Dundas Granite. These pegmatites appear to resemble the Greenbushes pegmatites in as far as there is no quartz-core development, and virtually no low-grade tantalum zones are present. This is demonstrated by the fact that greater than 95% of the assays are in the range 0.01 – 0.05% Ta_2O_5 (Tantalum Australia NL, 2002b).

Tin mining commenced in the area in the mid-1960s and the first parcel of 7.0 t of tin concentrate was recorded between 1965 and 1967 from Daves Claim. Mining continued sporadically until the early 1980s. Between 1966 and 1985, Mount Deans was prospected by Norseman Goldmines, Australian Tin and Tantalite, and CRA Exploration and, despite the presence of old tin–tantalum operations such as Daves Claim and Poldarks Opencut, geochemical results and resource evaluation suggested no further investigation of the area was warranted.

Over many years of exploration, a number of substantial pegmatite bodies have been identified with strike lengths in the order of 500–2000 m. In the northern half of the area, the pegmatites tend to be steeply dipping (30–90°), with an average dip of 60° and thicknesses ranging from 0.3 to 7.5 m. In the central and southern half of the area, dips are generally shallower (5–70°) and average 30°, with thicknesses of 0.3 – 8.0 m (Marshall, 1985). The shallowly dipping pegmatite at Poldarks Opencut is shown in Figure 100.

Almost all the pegmatites in the swarm have a common mineralogy typified by massive cleavelandite, and quartz, lepidolite and zinnwaldite. Coarse banding is common in many places. Cleavelandite is often present as large, subrounded, crystalline masses greater than

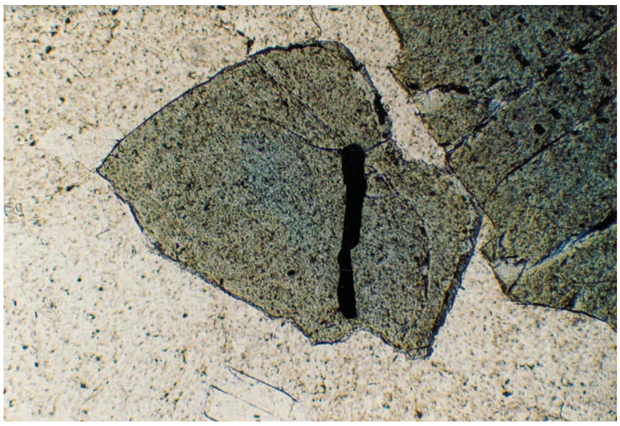

Figure 97. Tantalite occurring as an exsolved bleb within tourmaline and forming a slightly bent rod 0.4 mm in length (plane polars × 100; after Wilde, 1990)

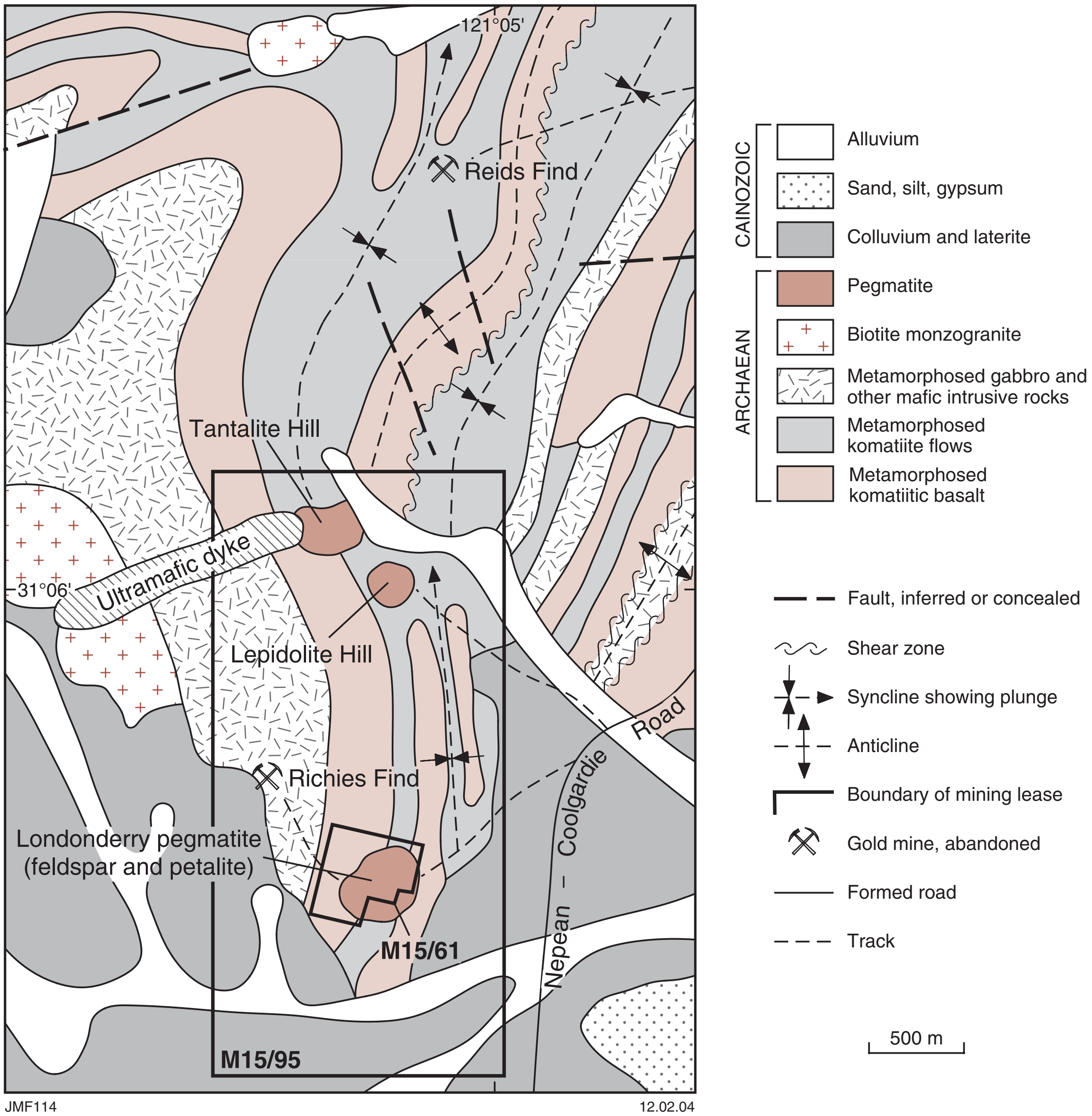

Figure 98. The geology of the area surrounding the pegmatites at Londonderry (modified from Fetherston et al., 1999)

Table 32. Zonation pattern in the Tantalite Hill pegmatite

Zone	*Mineral assemblage*
Border zone	Albite–quartz–garnet
Wall zone	Albite–quartz
Intermediate zones	Quartz–albite–microcline Albite–quartz–zinnwaldite Albite–quartz–lepidolite Quartz–microcline–petalite
Core zone	Quartz

SOURCE: Cross (1993)

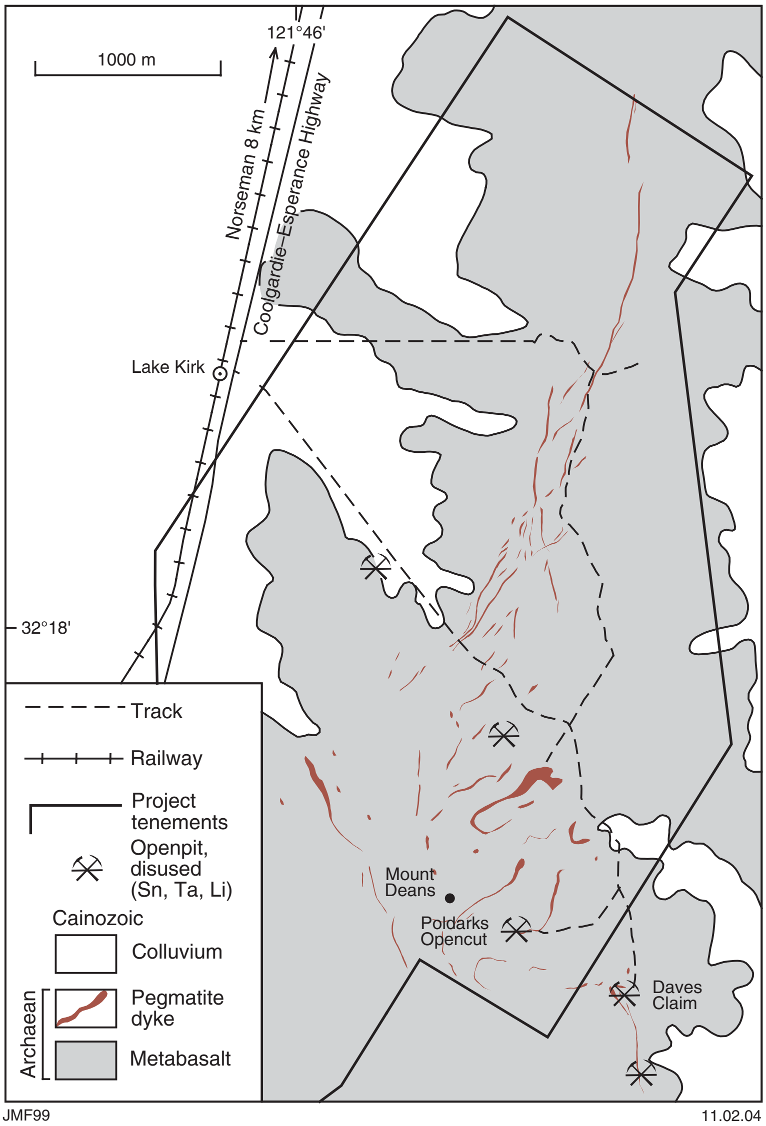

Figure 99. Geology of the area around Mount Deans (data courtesy Tantalum Australia NL)

Figure 100. Shallowly dipping pegmatite at Poldarks Opencut at Mount Deans. Pegmatite is about 1.25 m thick and is hosted by weathered metabasalt

15 cm in diameter that may be surrounded by prominent bands of lepidolite, mica, or very coarse, semi-rounded to subangular quartz (Figs 101 and 102). Other accessory minerals present include tourmaline, fluorite, beryl, petalite, and spodumene. The ore minerals are cassiterite and tantalite.

At Daves Claim, coarse brownish-black cassiterite crystals up to 30 mm in length are present within massive cleavelandite. Marshall (1985) noted that it is the cleavelandite-rich and quartz-poor margins of the pegmatites that appear to contain most of the cassiterite–tantalite mineralization. An example of the mineral distribution within a pegmatite may be seen in the cross section through Daves Claim that shows the distribution of Ta_2O_5 grades (Fig. 103). The highest grade (0.081% Ta_2O_5) is closest to the contact with the metabasalt host rock on the eastern margin and probably reflects a zonation pattern within the pegmatite. Analytical results of a cleavelandite–quartz–mica specimen collected by the author from Daves Claim yielded 246 ppm Ta, 182 ppm Nb, 470 ppm Sn, 2695 ppm Li, and 4014 ppm Rb respectively.

In 2001, Australasian Gold Mines (now Tantalum Australia) concluded an agreement with Kinross Gold Australia to purchase the Mount Deans prospecting licences to further evaluate the tantalum potential of the area.

Since 2001, Tantalum Australia have carried out a number of rock-chip sampling and drilling programs, and in 2002 it was announced that the area investigated contained estimated, indicated, and inferred resources of 9.1 Mt at 0.022% Ta_2O_5, 0.060% Nb_2O_5, and 0.170% SnO_2, based on the results of 157 drillholes within 60 m of the surface. It is estimated that this resource would yield 1960 t of Ta_2O_5 (Tantalum Australia NL, 2002b).

Figure 101. Cleavelandite mass ringed by zones of lepidolite (mauve) and radial masses of black mica at Poldarks Opencut, Mount Deans

Currently, metallurgical testing of ore samples obtained from the latest drilling program is underway at the company's mineral-dressing plant in Perth. To date, tests on the Mount Deans ore indicate Ta_2O_5 recoveries of up

Figure 102. Large, subrounded cleavelandite crystalline mass (centre right) surrounded by a fine-grained, black mica zone and an outer zone of very coarse, subrounded to subangular quartz at Daves Claim, Mount Deans

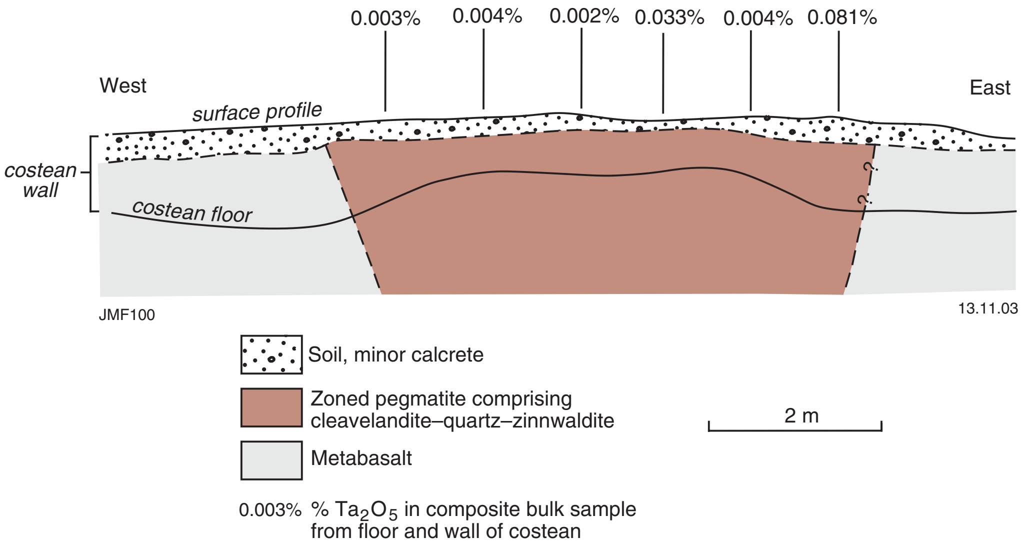

Figure 103. East–west cross section across Daves Claim at Mount Deans showing distribution of Ta_2O_5 grades (modified from Marshall, 1982b)

to 55% can be achieved, from material crushed to about 1.0 mm, after a single pass over a spiral concentrator. Testing is continuing.

As previously mentioned, Tantalum Australia has proposed that future development of the Mount Deans deposit may be linked to the development of their tantalum deposit at Binneringie by using a common primary-concentration plant for both deposits (Holland, 2002). It has been sugested that the company's existing milling plant at Norseman could be upgraded for the purpose.

Mount Weld

The Mount Weld carbonatite is located in the Eastern Goldfields, about 35 km south-southeast of Laverton. The carbonatite was first located by a regional airborne-aeromagnetic survey flown by the Australian Bureau of Mineral Resources in 1966. A large magnetic anomaly detected by the survey indicated the presence of a large circular structure beneath 20–25 m of alluvial sediments and 0–70 m of Tertiary lacustrine clays. The presence of the carbonatite plug was confirmed by Utah Development in a diamond and percussion drilling program in 1967. However, no economic mineralization was detected. It was not until 1981–84 that Union Oil Development Corporation outlined major phosphate, rare earth, and tantalum–niobium resources in the carbonatite regolith and sediments overlying the carbonatite plug.

The Mount Weld structure is a circular Palaeoproterozic volcanic diatreme about 3 km in diameter intruding a succession of Archaean greenstones that consist mainly of metasedimentary and metavolcanic rocks (Fig. 104). Duncan (1990) estimated that during its long history about four vertical kilometres of the carbonatite plug and surrounding greenstone rocks have been removed by erosional processes.

In the unweathered carbonatite plug, tantalum and niobium both occur in the calcium-niobate mineral pyrochlore (Fig. 5). This mineral is evenly distributed throughout the carbonatite, usually at low levels. Pyrochlore also varies widely in its composition, from an almost pure niobian variety to reddish and dark-amber tantalum and/or uranium varieties.

In its more recent geological history, especially during the Cainozoic, this carbonatite plug that is essentially composed of calcite and other soluble carbonate minerals has been subjected to deep weathering processes, largely by groundwater solution. These processes have resulted in the internal collapse of the upper section of the plug and subsequent concentration of large volumes of resistate minerals such as apatite, magnetite, pyrochlore, and vermiculite into a residual zone 10–70 m thick overlying the karstic surface of the unweathered carbonatite. Although the residual zone is host to a large phosphate deposit with inferred resources of 250 Mt at 18.1% P_2O_5, its tantalum–niobium resource is comparatively low grade, with pyrochlore mineralization rarely showing grades of 1.0% Nb_2O_5 and 0.02% Ta_2O_5 (Duncan, 1990).

Higher up in the regolith there is a sharp semi-horizontal contact with an overlying supergene zone. Supergene weathering of residual minerals in situ is found in a number of environments in this upper zone. These are located above a palaeogroundwater table within a colluvial soil profile, and in shallow lacustrine sediments containing variable proportions of carbonatite-derived materials. The upper regolith zone contains discrete deposits of rare earths, and tantalum–niobium minerals. It is here that the highest grades of tantalum–niobium mineralization are present in horizontal units that are 6–15 m thick and composed of unconsolidated, fine-grained, highly phosphatic lacustrine sediments grading upwards into externally derived smectite clays (Fig. 104).

Mineralogical studies have shown the phosphatic sediments to consist largely of very soft, friable, fine-grained to amorphous crandallite, together with the rare earth-enriched mineral florencite, and the barium and strontium varieties gorceixite and goyazite respectively. The mineralization contained in this horizon appears to have been derived by weathering of fine-grained detrital apatite and pyrochlore deposited in the deeper parts of broad palaeodrainage channels. This is evident from the common occurrence of crandallite pseudomorphs after pyrochlore. Scanning electron microscope studies have shown that some of the tantalum and niobium have since been leached from the crandallite and redeposited into secondary oxides of iron, manganese, and titanium.

In the early 1980s, over 300 vertical-aircore exploration drillholes were drilled over 10 km^2 of the carbonatite. This exploration resulted in the identification of the Crown, Anchor, and Coors tantalum–niobium deposits contained mainly in palaeolake sediments, and other zones of supergene weathering in situ in the upper regolith (Fig. 104). Total inferred tantalum and niobium resources were estimated at 145 Mt at 0.034% Ta_2O_5 and 273 Mt at 0.9% Nb_2O_5, using 0.02% and 0.5% cut-off grades respectively (Duncan, 1990).

The current owner of the Mount Weld rare earth and tantalum–niobium deposits, Lynas Corporation, has recently carried out a new evaluation of the Crown deposit. These studies, in the form of close-spaced drilling, bulk sampling, and analytical work for process testing, have indicated the presence of high-grade zones within the deposit that contain slightly more than 0.10% Ta_2O_5 and 3.20% Nb_2O_5 (Lynas Corporation Limited, 2002, pers. comm.).

Despite the presence of a large high-grade and easily accessible tantalum–niobium resource at Mount Weld, considerable research is required into the mineral and physical upgrading of the ore to produce tantalum and niobium concentrates acceptable to downstream metal refiners. With this in mind, Lynas Corporation has focused its attention on first developing the Mount Weld rare earths deposit by employing advanced Chinese phosphate-flotation technology, with the aim of commencing production in mid-2004. The company expects to commence a similar research and development program for the tantalum and niobium resources in future years.

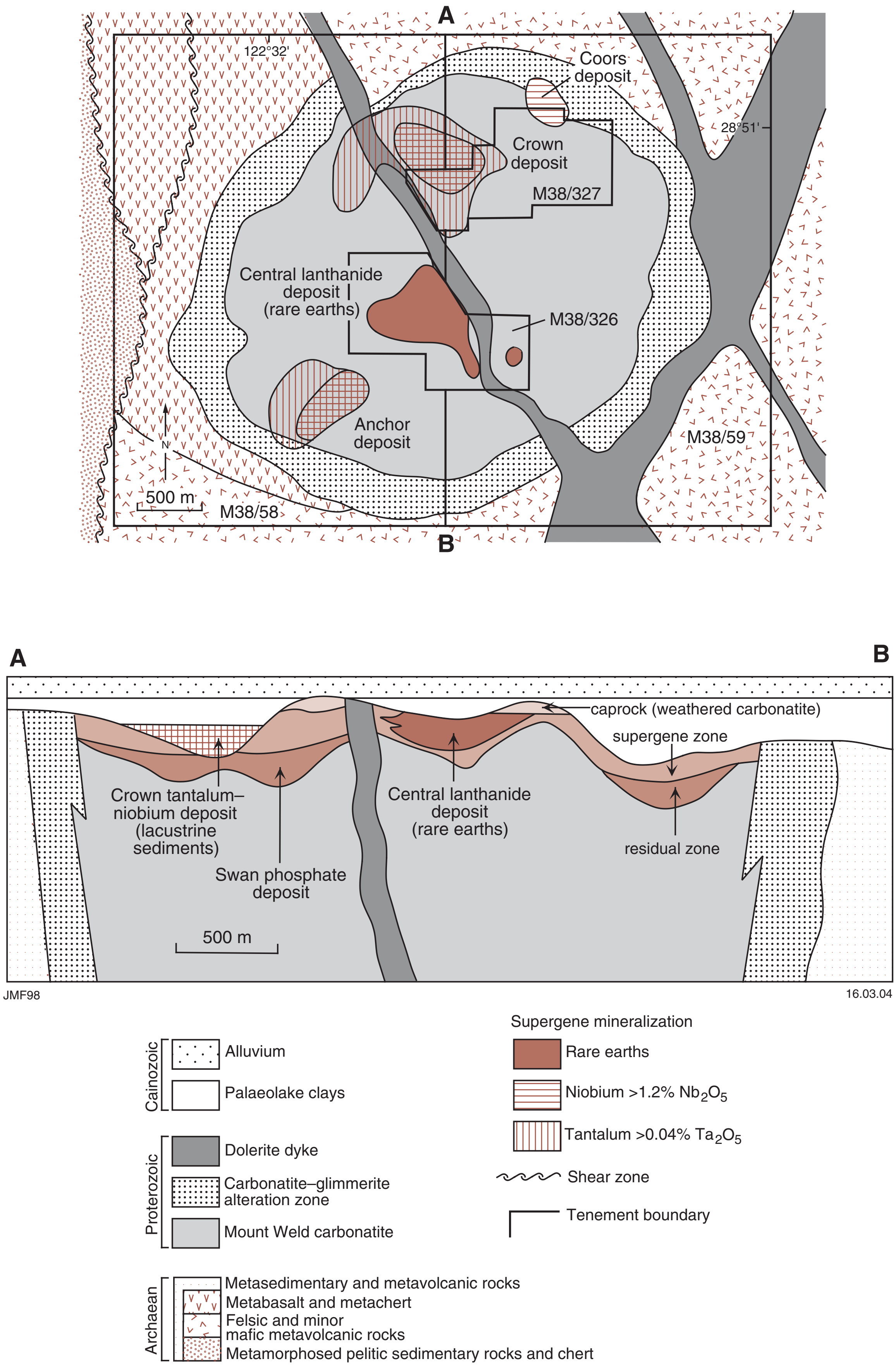

Figure 104. Geological map and cross section of the Mount Weld polymetallic carbonatite deposit (data courtesy Lynas Corporation Ltd)

Paynes Find

Mount Edon North

A swarm of about 20 pegmatites hosted by Archaean greenstones, mainly amphibolites, is located to the northeast of Mount Edon, about 5 km south of Paynes Find in the Murchison region. In the past, this deposit has yielded about 30 kg of tantalocolumbite from eluvial material eroded from the pegmatites (Lipple et al., 1983).

In May 2002, Haddington International Resources undertook a drilling program in the area to evaluate the pegmatites' tantalum potential after earlier pegmatite channel samples had yielded up to 0.076% Ta_2O_5 over 20 m. The program was designed to test about 500 m of the largest pegmatite in the swarm. Fourteen reverse-circulation holes were drilled of which 11 penetrated the pegmatite. Results showed the pegmatite to be a thick tabular body (up to 42 m thick) dipping 40° to the east, and anomalous in lithium and rubidium.

Assays of drillhole samples revealed that the overall Ta_2O_5 grade was too low for economic recovery. Areas of strongest mineralization yielded 0.010 – 0.028% Ta_2O_5 + Nb_2O_5 over 14 m with average values around 0.017% Ta_2O_5. The highest Ta_2O_5 value recorded was 0.034% over 1.0 m. Despite these results, it is believed that other pegmatites in the Paynes Find area may have potential for economic tantalite deposits and the company intends carrying out further investigations in future years (Minmet Ozmine, 2002g).

Yalgoo

Johnsons Well

Situated about 115 km west-southwest of Mount Magnet in the Murchison region, the Johnsons Well pegmatite deposit was explored by Tantalum Australia in 2002. The deposit comprises two pegmatites similar to those at Mount Deans near Norseman. The Johnsons Well pegmatites are hosted by Archaean felsic metavolcanic rocks. They dip to the north at approximately 10–15°, with a east–west strike length of about 800–1000 m and an average thickness of 3.0 m (maximum 4.0 m). The highly fractionated pegmatites are lithium- and rubidium-rich and are composed of mainly massive cleavelandite with lepidolite and an unusual variety of blue muscovite.

During its investigations, Tantalum Australia drilled 54 holes over a 700 m strike length. Significant drillhole intercepts included 4.0 m at 0.042% Ta_2O_5 and 3.0 m at 0.032% Ta_2O_5. A total resource for the deposit to 10 m depth was estimated at 0.13 Mt at 0.019% Ta_2O_5. This incorporates a high-grade resource estimated at 32 000 t at 0.032% Ta_2O_5 (Tantalum Australia NL, 2002b).

Chapter 13

Summary

Tantalum is a very hard, dense, blue-grey, refractory metal with a cubic crystalline structure. It has a very high melting point of 2996°C, and is a good conductor of heat and electricity. Pure tantalum has a high tensile strength, is extremely malleable and ductile, and is easily worked into intricate forms at room temperature. It is almost completely immune to chemical attack below 150°C. At temperatures greater than or equal to 300–400°C tantalum reacts with oxygen and nitrogen. Tantalum combines readily with other refractory metals such as tungsten, titanium, and hafnium, forming super alloys.

Tantalum occurs naturally in a vast array of mainly oxide minerals. Due to their similar physical properties, tantalum and niobium (also known as columbium) occur together in many minerals, most commonly the columbite–tantalite group, with the mineral tantalite being the most widespread and important ore of tantalum. Other important tantalum ore minerals mined in Western Australia include manganotantalite, wodginite, stibiotantalite, and microlite.

Tantalum was discovered by Anders Ekeberg in 1802, but it was not until 1903 that the first relatively pure metal was produced. In 1905, the first commercial use of tantalum began in Germany with the invention of tantalum metal filaments for use in incandescent light globes. This application was short-lived, as by 1912 tantalum filaments had been replaced by tungsten. Over the next 30 years applications for tantalum were found in the metallurgical and chemical industries with the development of special alloys and corrosion-resistant chemical processing equipment. In 1929, tantalum carbide, one of the hardest artificial substances known to man, was developed for use in cutting tools.

During the Second World War, tantalum capacitors were invented for use in military communication and early radar equipment. At that time, Australia was the world's largest tantalum producer. In the 1980s, demand for tantalum accelerated rapidly, with the invention of the microchip tantalum capacitor leading to its widespread application in computers, communications, and other electronic equipment. It was this impetus that led to the development of hard-rock tantalum mining and the evolution of the large-scale openpits in operation today, notably in Western Australia.

In Western Australia, tantalum is found in three distinct primary mineralization styles. Of these, granitic rare-metal pegmatites are almost exclusively the dominant style, with the only exceptions being the carbonatite style of the Mount Weld deposit, and the subalkaline granite–syenite style of the Brockman deposit. Economic tantalum mineralization is mostly found in highly fractionated granitic rare-metal pegmatites commonly derived from late Archaean granites. These pegmatites are often situated on regional shears that are usually hosted by greenstone rocks within 5–10 km from the parent granite. Fractionated pegmatites may contain multiple concentric zones, or stacked sheets containing areas of discrete mineralization rich in tantalum, tin, niobium, lithium, beryllium, and caesium. In Western Australia, most pegmatites have been subjected to deep weathering and extensive kaolinization up to 80 m below surface. In many areas, weathering and erosional processes have formed economic eluvial, colluvial, and alluvial placer tantalum deposits.

Currently, Western Australia has four operating tantalum mines. The huge Greenbushes and Wodgina mines are respectively, the largest and second-largest tantalum operations in the world, with combined reserves and resources totalling over 310 Mt at an average grade of 0.025% Ta_2O_5. Two other mines are located at Bald Hill in the Eastern Goldfields, and at Dalgaranga near Mount Magnet. It is estimated that Western Australia has at least 75% of presently defined global tantalum reserves at 152.1 Mt at 0.028% Ta_2O_5 and containing almost 43 140 t Ta_2O_5. Other countries with defined global resources are Canada with 8%, and Brazil with 5%. Other countries, including China, the Russian Federation, and numerous African countries, are estimated to contain reserves totalling 12%.

Tantalite ore is processed into export-grade concentrate averaging 30–35% Ta_2O_5. In 2001, Western Australia exported 806 t of concentrate, valued at A$176.3 million, primarily to the USA, Germany, and Japan for processing into tantalum metal and powder.

Tantalum metal is used in the chemical industry for its anti-corrosive properties, and as tantalum carbide in metal cutting and machining. It has also found new applications in the aerospace and power-generation industries in super alloys, and in medicine and dentistry. The bulk of Ta_2O_5 high-grade concentrate is used in the manufacture of high-purity tantalum powder primarily for the manufacture of tantalum capacitors required by the electronics and telecommunications industries. Due to their small size and high reliability, these capacitors are used in miniaturized circuits of computerized equipment, with an estimated 35% of total production for use in mobile phones. In 2000, it was estimated that tantalum usage in the electronics industry dominated the market with a 61% share. This was followed by mill products at about 15%, super alloys at 10%, metal cutting carbides at 8%, and tantalum chemicals at 6%.

Since 1980, tantalum has been subject to a number of periods of increased demand and rapid price escalations, which have been followed by rapid reversals in demand and a subsequent crash in price. This volatility in the market was originally attributed to panic buying and inventory hoarding in times of short supply. Today, the market is also affected by changes in demand by the electronics industry. This was effectively demonstrated by the all-time-high spot price of greater than A$770/kg reached in 2000, which was soon followed by a rapid fall off in demand and subsequent price crash in 2002 to levels of around A$86–107/kg. Since that time there have been indications of a modest resurgence in demand.

Western Australia, has numerous highly prospective areas for future development of tantalum resources. Many of these areas in the south of the State such as Cattlin Creek, North Ravensthorpe, Binneringie, Mount Deans, and extensions to Bald Hill have already been fully or partially explored. In the north of the State, areas around Dalgaranga, Arthur River, and in the Pilbara region, particularly in the Wodgina area, already have established resources or demonstrated high prospectivity. The large tantalum resources contained in the Mount Weld and Brockman deposits await the development of improved ore-processing technology.

With the probable return to increased shipments of tantalum concentrates in 2003, it is expected that new innovations in the expanding electronics and communications industries should provide the necessary impetus for a resurgence in demand, together with increased prices, within a few years. At that time, the State's existing tantalum operations, plus many areas prospective for tantalum, will be at the forefront of future exploration and development to maintain Western Australia's position of world leader in the mining and processing of this high-tech metal.

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Appendix 1

Key websites accessed for this publication

Accumet Materials Co.	www.accumetmaterials.com
Alkane Exploration Ltd	www.alkane.com.au/zirconia.html
Ames Laboratory	www.ameslab.gov/RIC/Sept98News.html
Angus & Ross plc	www.angusandross.com
Avalon Ventures Ltd	www.avalonventures.com
AVX Corporation	www.avxcorp.com
Bisnis	www.bisnis.doc.gov
British Columbia Geological Survey	www.em.gov.bc.ca/mining/geolsurv/publications
Cabot Corporation	w1.cabot-corp.com
Central African Mining and Exlploration Co. plc	www.camec-plc.com
Cerac Inc.	www.cerac.com
Chapleau Resources	www.chapleauresources.com
China Market	www.chinamarket.com.cn/C/invest/tongliao
Cometec	www.cometec.com
Commerce Resources Corp.	www.commerceresources.com
Department of Industry and Resources, Western Australia	www.doir.wa.gov.au
Egyptian Geological Survey and Mining Authority	www.egsma.gov.eg
Electronic Alloys UK	www.aircraftmaterialsuk.com/data/electronic
EMI Placer Stockfile	www.mine.mn/Placer_Stockfile.htm
Espi Metals	www.espi-metals.com
Geolisting.com	www.geolisting.com
Geolite	www.geolite.com
Gippsland Limited	www.gippslandltd.com.au
Glengarry Resources Limited	www.glengarrynl.com.au
Goldstake Explorations Inc.	www.goldstake.com
Goodfellow	www.goodfellow.com
Guyana Geology and Mines Commission	www.sdnp.org.gy/ggmc
Haddington Resources Limited	www.haddington.com.au
H. C. Starck	www.hcstarck.com
Houston Lake Mining Inc.	www.houstonlakemining.com
Julia Corporation Limited	www.juliacorp.com
Kanowna Lights Limited	www.kanownalights.com.au
Kemet Corporation	www.kemet.com
Kermode Resources Ltd	www.kermode.com
Linear Resources Inc.	www.linearresources.com
Manitoba Geological Survey	www.gov.mb.ca/itm/mrd/geo/
MBendi	www.mbendi.co.za
Metal Mining Agency of Japan	www.mmaj.go.jp/mmaj_e/project/asia/thailand.html
Metal Suppliers Online	www.suppliersonline.com
Metallurg	www.metallurg.com
Mineral Resources Authority of Mongolia	www.mram.mn
Minerals and Geoscience Department Malaysia	www.jmg.gov.my
Minesite.com	www.minesite.com
MiningNews.net	www.miningnews.net
Minmet Ozmine	www.ozmine.com.au
NASA Ultra-efficient Engine Technology Program	www.ueet.nasa.gov/engines101.php
National Department of Mineral Production Brazil	www.dnpm.gov.br
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Naval Research Laboratory (USA)	http://mstd.nrl.navy.mil
Navigator Exploration Corp.	www.navigatorexploration.com
New Millennium Resources NL	www.new-millennium.com.au
Ningxia Non-ferrous Metals Smeltery	www.nniec.com
Paranapanema SA	www.mamore.net
Platinova A/S	www.platinova.com
Principal Metals	www.principalmetals.com
Process Materials	www.processmaterials.com/borides.html
Reade Advanced Materials	www.reade.com/products/product_index.html
RND Korea	www.rndkorea.co.kr
Scientific Instrument Services Inc.	www.sisweb.com
Sons of Gwalia Ltd	www.sog.com.au
Spectrum Laboratories Inc.	www.speclab.com/elements
Stanford Materials Corporation	www.stanfordmaterials.com
Tantalum Australia NL	www.tantalumaustralia.com
Tantalum–Niobium International Study Center	www.tanb.org
Tertiary Minerals plc	www.tertiaryminerals.com
The Rembar Company Inc.	www.rembar.com
The Valve Page	www.thevalvepage.com
TT Electronics	www.welwyn-tt.co.uk

TTI Market Eye	www.ttiinc.com/marketeye
Ulba Metallurgical Plant	www.ulba.kz/eng/
U. S. Geological Survey Mineral Information	http://minerals.usgs.gov/minerals/pubs/country
Vishay Intertechnology	www.vishay.com
WebElements Periodic Table	www.webelements.com
Wilshire Chemical Co. Inc.	http://users.aol.com/wilshrchem/electronic.htm

Appendix 2

Index of Western Australian localities

Appendix 3

Other tantalum deposits, prospects, and occurrences in Western Australia

Deposit/prospect/ locality	*Location* Latitude (S)	*Location* Longitude (E)	*Comments*	*Data source*
Albany–Fraser Orogen				
Bellinger [a] Locality	33°45'00"	123°33'00"	Pegmatite veins in granite containing mica, and ferrotantalite–manganocolumbite ranging from 75–15% Ta_2O_5	Miles et al., 1945
Capricorn Orogen				
Marloo Well 1 Locality	24°40'59"	115°48'04"	Columbite–tantalite mineralization in pegmatite	A31555
Marloo Well 2 Locality	24°45'18"	115°51'57"	Columbite–tantalite mineralization in pegmatite. Also contains beryl and REE	A31555
Morrissey Hill Prospect	24°32'48"	116°11'19"	Pegmatite and eluvial material. Assay values of 34.5% Ta_2O_5 and 47.2% Nb_2O_5 from 400 kg sample	A31555
Mount Alexander Prospect	22°37'36"	115°30'00"	Alluvial/eluvial (Ta). Contains tin–tantalum panned concentrates of 1.1% SnO_2 and 0.5% Ta_2O_5	A28127
Wabli Creek Prospect	24°53'38"	116°16'08"	2–5% grade of recoverable minerals was recorded for a zoned pegmatite. One tonne of samarksite mined from location	A31555
Halls Creek Orogen and Hooper Complex				
Collier Bay[b] Locality	16°34'00"	124°12'00"	Ta-rich ore assaying 68% Ta_2O_5 collected in the area	Miles et al., 1945
Frog Creek Prospect	18°56'56"	127°15'32"	Alluvial/eluvial: panned concentrates assayed up to 4500 ppm W, 1650 ppm Sn, 1900 ppm Ta, and 8.1 ppm Au	A37212
Junda 2 Prospect	18°49'26"	127°17'35"	Panned concentrate assayed 1.85% Ta, 7250 ppm Nb, 7200 ppm Sn, and 7700 ppm W	Hassan, 2000, A13238
Junda 3 Prospect	18°49'23"	127°17'35"	Pegmatite vein assayed 240 ppm Ta and 20 ppm Nb	Hassan, 2000
Junda 4 Prospect	18°49'34"	127°16'48"	Panned concentrate assayed 2500 ppm Ta, 1140 ppm Nb, 3150 ppm Sn, and 3200 ppm W	Hassan, 2000
Minneroo Pool (Cummins Range) Prospect	19°01'12"	127°11'35"	Thin northeast-trending, tin–tantalum-bearing pegmatites close to northeasterly trending fault. Rock-chip samples of pegmatite contained up to 400 ppm Sn, 20 ppm Ta, and 50 ppm Nb	A13931; Sanders, 1999; Hassan, 2000
Minneroo Pool (Christmas Creek) Prospect	19°01'12"	127°11'42"	Alluvial/eluvial: panned concentrates assayed up to 1.7% Sn, 0.37% Ta, and 0.1% Nb	A13931; Sanders, 1999; Hassan, 2000
Mount Dockrell[a] Locality	18°51'25"	127°17'54"	Two alluvial samples of tin ore collected in the headwaters of Willy Willy Creek contained 72–74% cassiterite and 20–26% tantalite	Simpson, 1952
Mount Heartbreak B/Columbium Creek/Mount Dockrell Prospect	18°54'50"	127°14'31"	Alluvial tin. Concentrate of 0.55 kg/m^3 at 20.0% $(Ta,Nb)_2O_5$	Miles et al., 1945; Hassan, 2000; A11564; A14837; A17190; A19740; A37212; A38300

Deposit/prospect/ locality	Location Latitude (S)	Longitude (E)	Comments	Data source
Mount Heartbreak C/Columbium Creek/Mount Dockrell				
Prospect	18°54'47"	127°13'59"	Alluvial tin. Concentrate of 0.19 kg/m3 at 22.3% $(Ta,Nb)_2O_5$	Hassan, 2000; A11564; A14837; A17190; A19740; A37212; A38300
Mount Heartbreak D/Columbium Creek/Mount Dockrell				
Prospect	18°56'06"	127°12'47"	Alluvial tin. Concentrate of 0.06 kg/m3 at 72.4% $(Ta,Nb)_2O_5$	Hassan, 2000; A11564; A14837; A17190; A19740; A37212; A3830
Mount Heartbreak E/Columbium Creek/Taylor Lookout				
Prospect	18°55'44"	127°14'31"	Alluvial tin. Concentrate 0.10 kg/m^3 at 27.9% $(Ta,Nb)_2O_5$. Pegmatite with scattered crystals of spodumene, beryl, columbite, and cassiterite	Hassan, 2000; A9092; A11564; A14837; A17190; A19740; A37212; A38300
Mount Remarkable				
Prospect	17°11'53"	127°36'25"	Alluvial/eluvial. Panned concentrates 0.66% Sn, 0.55% Ta, and 0.43% Nb	A10201
Richenda River				
Prospect	17°25'34"	125°22'44"	Tin and tantalum minerals are common accessories in all creeks draining the granite. A small tin plant operated here between 1984 and 1985, but there is no record of production	A22998
South Dockrell				
Prospect	18°47'53"	127°12'43"	Alluvial/eluvial. Nearby creeks contain scheelite and cassiterite with tantalite inclusions; up to 1.1% Ta in panned concentrates	A11170; A13684

Pilbara Craton

Deposit/prospect/ locality	Latitude (S)	Longitude (E)	Comments	Data source
Biscay Well/Turkey Camp Well				
Locality	20°44'56"	119°07'12"	Beryl and Ta. Area contains two Ta-bearing pegmatites in granite	Quantum Resources Limited, 2001
Bore Creek				
Deposit	20°37'23"	118°41'35"	Alluvial/eluvial (Sn, Ta, Li). Probable reserves 0.18 Mt	S2101
Breaker Inlet				
Prospect	20°00'35"	119°10'00"	Estuary placer (Sn, Ta). Four low-grade intersections with 5–33 g/m^3 Sn and 1.5–6.6 g/m^3 Ta in river gravels and clays	Marshall, 1982
Breens				
Deposit	21°36'53"	119°32'55"	Alluvial/eluvial (Sn, Ta, Li). Estimated combined resources for Breens/Coomba Creek: 98 438 t at 0.109% SnO_2 and 0.007% Ta_2O_5	A24569
Chinnamon Creek				
Prospect	21°01'34"	118°42'43"	Pegmatite associated with the Numbana Granite containing 28.3% Ta and 28.3% Nb	A25072; A25073
Coffin Bore North				
Locality	21°03'55"	118°53'16"	Old workings for ?Ta, probably in pegmatite within undifferentiated mafic schists	A5570
Coffin Bore Northeast 1				
Locality	21°04'24"	118°53'43"	Old workings for Ta, probably in pegmatite within mafic schists	A5570
Coffin Bore Northeast 2				
Locality	21°04'25"	118°53'58"	Old workings for ?Ta, presumably in pegmatite; within serpentinite	A5570
Combos				
Prospect	21°36'39"	119°29'01"	Open-pittable Sn and Ta deposit in present drainage alluvials	S2347; A19220
Cooglegong				
Deposit	21°32'36"	119°21'23"	Alluvial/eluvial (Sn, Ta, Li). Inferred resources of 0.592 Mt at 0.003% Ta_2O_5	S2345; A24569
Cooglegong				
Locality	21°37'08"	119°25'52"	Pegmatite (Sn, Ta)	A8135; Blockley, 1980

Deposit/prospect/ locality	*Location* Latitude (S)	Longitude (E)	*Comments*	*Data source*
Cooglegong Creek Deposit	21°35'07"	119°29'26"	Alluvial/eluvial (Sn, Ta, Li). Indicated resources of 0.026 Mt at 0.003% Ta_2O_5	A24569
Coomba Creek Deposit	21°37'13"	119°33'40"	Alluvial/eluvial (Sn, Ta). Estimated combined resources for Breens/Coomba Creek: 98 438 t at 0.109% SnO_2 and 0.007% Ta_2O_5	S3492; A24569; Blockley,1980
Coonarie Creek Location	21°46'06"	118°56'03"	Alluvial/eluvial (Sn, Ta)	A6432
Coondina Deposit	21°53'32"	119°23'12"	Alluvial/eluvial (Sn, Ta, Li). Inferred resources of 0.408 Mt at 0.001% Ta_2O_5	S1782; A24569
Crawfords/Tabba Tabba Prospect	20°39'14"	118°54'54"	Ta prospect 1.6 km northwest of Tabba Tabba main workings. Comprises four pegmatites containing grey tantalite previously worked in shallow opencuts	Finucane and Telford, 1939
Curlew/Hillside Deposit	21°34'29"	119°17'29"	Alluvial/eluvial. Inferred resources of 0.082 Mt at 0.002% Ta_2O_5	A11694
Eight Mile Creek Prospect	21°09'01"	119°58'11"	Workings in Eight Mile Creek for alluvial tin with high tantalite content. Close to tin-bearing pegmatites in gneissic and foliated granite	Blockley, 1980
Eleys Creek Deposit	21°39'05"	119°29'57"	Alluvial/eluvial (Sn, Ta). Indicated resources of 0.072 Mt at 0.002% Ta_2O_5	A4779; A24569
Ellis/Crawfords Prospect	20°39'40"	118°55'30"	Pegmatite at the head of a short NW-trending gully, situated on a fault plane dipping 20° west. Albite, sericitic mica, quartz with spessartine garnet, magnetite, tantalite, microcline, and some cassiterite; within amphibolite. Alluvial mining in sediments below	Ellis, 1950
Five Mile Creek Deposit	21°39'21"	119°24'56"	Alluvial/eluvial (Sn, Ta, Li). Estimated reserves of 0.038 Mt at 0.060% SnO_2 and 0.024% Ta_2O_5	Blockley, 1980; A49320
Hartigans Deposit	21°31'07"	119°32'52"	Alluvial/eluvial (Sn, Ta, Li). Inferred resources of 0.362 Mt at 0.005% Ta_2O_5	Blockley, 1980; S1785; A2976; A24569
Hillside Deposit	21°42'30"	119°26'35"	Alluvial/eluvial (Sn, Ta, Li). Estimated resources of 0.155 Mt at 0.910% SnO_2 and 0.004% Ta_2O_5. Detrital microlite occurs in pebbly alluvium 6.4 km northwest of Hillside Homestead	Simpson, 1952; A24569
Kangan Prospect	21°05'10"	118°30'54"	Sn and Ta. Angular pebbles of ?tapiolite assayed 78% Ta_2O_5. Old workings for Sn and Ta in pegmatite within metasediments of the De Grey Group	Miles et al., 1945; Hickman and Lipple, 1978
Kookynie/Shaw River Deposit	21°36'55"	119°22'05"	Alluvial (Sn, Ta). Indicated and inferred resources of 0.072 Mt at 0.023% Ta_2O_5	S2359
Lalla Rookh (Tabba)[(a)] Locality	20°49'49"	118°53'39"	Tantalite specimen (probably manganotantalite) collected 25.7 km northwest of Lalla Rookh assayed at 70% Ta_2O_5 and 5% Nb_2O_5	Simpson, 1952
Lynas Find Locality	21°00'45"	118°55'20"	Alluvial/eluvial (Sn, Ta, Li)	S2355
McPhees Northwest Locality	20°59'59"	118°55'48"	Au, ?Ta. Old workings in ?mafic rocks covered by scree	A3663

Deposit/prospect/ locality	Location Latitude (S)	Longitude (E)	Comments	Data source
McPhees Southwest Locality	21°00'20"	118°55'33"	Au, ?Ta. Old workings in ?mafic rocks covered by scree	A3663
Moolyella Deposit	21°10'12"	119°55'22"	Alluvial/eluvial (Sn, Ta). Inferred resources of 4.5 Mt at 0.003% Ta_2O_5. 8 km north of Moolyella a microcline–albite pegmatite contained manganotantalite whose concentrates assayed 63% Ta_2O_5, 7% Nb_2O_5, and 3% Sn. Total recorded tantalite–columbite production 141.5 t	S1360; A38076; A39284; A11439; A11440; A16409; Simpson, 1952; Witt, 1990
Mount Hall Prospect	20°48'56"	117°11'59"	Pegmatite dykes containing beryl, tantalite, and spodumene. 1960s minor production of 3.34 t of tantalite and 5.26 t of tantalite–columbite containing 1.04 t Ta_2O_5 and 2.46 t $(Ta, Nb)_2O_5$. Most of the production from alluvial/eluvial deposits	Hickman, 1983
Mount Spinifex Prospect	20°45'45"	118°15'00"	Alluvial/eluvial (Ta, Sn, Au). Drill samples with maximum values of 600 ppm Sn, 230 ppm Ta, and 0.832 ppm Au	A11827
Mulgandinnah Deposit	21°30'26"	119°22'28"	Alluvial/eluvial (Sn, Ta). Indicated resources of 0.015 Mt at 0.002% Ta_2O_5	A24569
Mundine Well North 1 Locality	21°39'18"	119°06'22"	Cu and Ta workings plotted on Marble Bar 1:250 000 geological map	Hickman and Lipple, 1978
Mundine Well North 2 Locality	21°39'43"	119°06'07"	Ta workings plotted on Marble Bar 1:250 000 geological map	Hickman and Lipple, 1978
Mungaleena/Crawford Bore Deposit	20°49'19"	119°31'37"	Alluvial/eluvial. Inferred resources of 0.19 Mt at 0.004% Ta_2O_5 estimated from costeaning	A9135
Numbana Prospect	21°20'23"	118°37'58"	Beryl mined from a quartz-cored pegmatite associated with columbite and mica. Tantalum and tantalo-columbite were also mined mostly from alluvial placers and also probably from local pegmatites. Production for 1953–56 yielded 3.58 t of tantalocolumbite	A22034
Pegmatite Gully/Upper McDonald Lead Deposit	21°08'42"	119°53'46"	Cassiterite, tantalocolumbite, and magnetite in subparallel, shallow-dipping quartz–albite–microline pegmatites in clusters and up to 3 m wide and 300 m long. Located in biotite schist and felspar–biotite gneissic granite. Approximate resource of 13 200 m^3 Ta at an average grade of 2047 ppm	A11440
Pinga Creek Deposit	21°30'56"	118°49'01"	Alluvial/eluvial (Sn, Ta). Inferred resources of 0.165 Mt at 0.09% Ta_2O_5	S1421; Hickman and Lipple, 1978
Pinnacles/East Wodgina Deposit	21°10'18"	118°47'31"	Alluvial/eluvial (Ta, Nb). Estimated resource of 20 000 m^3 at 0.09% cassiterite and tantalite. Previous mining of 8.03 t cassiterite and 1.11 t tantalite	A11942
Pippingarra East Prospect	20°34'19"	118°46'12"	Ta, beryl. Production for 1953–57 was 6.66 t tantalocolumbite and 3.09 t tantalite	Hickman and Gibson, 1982a
Pippingarra West Prospect	20°34'23"	118°45'36"	Ta, beryl. Old workings in pegmatite that produced 0.03 t tantalite–columbite and 22.79 kg beryl	Hickman and Gibson, 1982a
Shaw River Deposit	21°42'53"	119°25'57"	Alluvial/eluvial (Sn, Ta). Indicated resources of 2.46 Mt at 0.003% Ta_2O_5. Total recorded tantalite–columbite production of 628.3 t	S1448; Witt, 1990

Deposit/prospect/ locality	Location Latitude (S)	Longitude (E)	Comments	Data source
Shaw River Alluvials Prospect	21°40'23"	119°28'55"	Alluvial. Panned concentrate with 3.99% Sn, 1816 ppm Ta, 594 ppm Nb, and 350 ppm Y	A40371
Shaw River Eluvials Prospect	21°32'50"	119°21'13"	Eluvial (Sn, Ta). Panned concentrates of 2.66% Sn, 2114 ppm Ta, 513 ppm Nb, and 676 ppm Y	A40371
South Ceremonial Dam Prospect	21°08'13"	119°54'18"	Cassiterite, tantalocolumbite, and magnetite in subparallel, shallow-dipping quartz–albite–microline pegmatites in clusters and up to 3 m wide and 300 m long. In biotite schist and felspar–biotite gneissic granite	A11440
Spear Hill Deposit	21°29'31"	119°24'51"	Alluvial/eluvial (Sn, Ta). Inferred resources of 0.159 Mt at 0.003% Ta_2O_5	S1778; A8135; A24569; A28386; Blockley, 1980
Spear Hill South Prospect	21°30'47"	119°25'26"	Alluvial Sn and Ta in eastern tributaries of Cooglegong Creek. Contains cassiterite, tantalite, fergusonite, yttrotantalite, and tanteuxenite	A47858
Split Rock[(a)] Prospect	21°33'10"	119°36'21"	Alluvial/eluvial (Ta, Sn). Angular pebbles of yttrotantalite (15%) and coarse detrital cassiterite (60%)	Miles et al., 1945
Stannum Alluvials 1 Locality	21°17'43"	118°33'42"	Alluvial/eluvial (Sn, Ta, Nb). Abandoned alluvial workings over granite	Hickman and Lipple, 1978
Stannum Alluvials 2 Prospect	21°14'31"	118°36'50"	Alluvial/eluvial (Sn, Ta). Tin and tantalite worked in small gullies to produce 4 t of tin concentrate and 2.8 t of tantalite	Miles et al., 1945; Blockley, 1971, 1980
Stannum West Prospect	21°14'17"	118°37'26"	Sn and Ta. Flat-lying pegmatite vein worked in two places 150 m apart for cassiterite and tantalite	Blockley, 1979, 1980
Tin Creek Locality	21°08'06"	118°41'59"	Alluvial/eluvial (Sn, Ta)	Blewett et al., 2001
Trig Hill Prospect	21°36'10"	119°17'21"	Alluvial/eluvial (Sn, Ta). Shutdown openpit	Hickman, 1983; A40371
Trig Well Prospect	20°55'34"	118°55'23"	Alluvial/eluvial (Sn, Ta). Tantalite grades of 0.22–0.40 kg/linear m^3. Tantalite sample assays of 32–52% Ta_2O_5	Hickman and Gibson, 1982b; A39508; A42817
Upper Five Mile Prospect	22°00'14"	120°13'19"	Alluvial tantalum–columbite and beryl workings. In 1955, 2.4 t of $(Ta,Nb)_2O_5$ was mined	Hickman, 1983; Blockley,1980
Western Shaw (Woodstock)[(a)] Prospect	22°05'00"	119°10'00"	Alluvial/eluvial (Ta, Sn). Gravel samples of manganotantalite, columbite, and some tapiolite, microlite, and cassiterite. One sample assayed 49.5% Ta_2O_5, 15.5% Nb_2O_5, and 8.6% SnO_2	Miles et al., 1945; Simpson, 1952

Yilgarn Craton

Deposit/prospect/ locality	Latitude (S)	Longitude (E)	Comments	Data source
Bogaloo Well Locality	27°28'08"	117°08'56"	Beryl, tantalum, and gemstones	A45014
Carnamah[(a)] Locality	29°41'37"	115°53'11"	Tantalite specimen collected 4.8 km from Carnamah contained 70% Ta_2O_5	Simpson, 1952
Choallie (Poona) Prospect	27°06'14"	117°27'13"	Pegmatites and quartz blows. Surface and mine-dump samples assayed 53–54% Ta_2O_5	WAMEX open-file correspondence, Item No I2989

Deposit/prospect/ locality	Location Latitude (S)	Longitude (E)	Comments	Data source
Coodardy				
Prospect	27°19'16"	117°40'59"	Eluvial tin-bearing albitic pegmatites (Sn, Nb, Ta). Eluvial manganocolumbite assayed 48–62% Nb_2O_5 and 18–34% Ta_2O_5	Miles et al., 1945
Edah				
Prospect	28°11'43"	117°04'26"	Alluvial/eluvial (Ta). Panned concentrates assayed 0.14% Ta_2O_5	A30399
Eight Mile Dam/Mount Belches				
Prospect	31°26'05"	122°07'20"	Pegmatites intruding Archaean metasedimentary rocks. Previously exploited for Li–bearing mica. Tantalite and cassiterite mineralizaton also present. Rock-chip sample assays for tantalum yielded 140 and 370 ppm	Painter and Groenewald, 2001; A36367; A38920
Ferndale (Balingup)[(a)]				
Prospect	33°49'45"	115°55'50"	Large pegmatite dykes, up to 200 m length and 90 m width, poorly differentiated with low values for Sn, Ta, and Nb. Contains minor manganocolumbite and beryl	Miles et al., 1945; A14402
Gibraltar				
Prospect	31°02'47"	120°57'44"	Two discrete granitic pegmatites. One contains manganotantalite with assay values of 53–60% Ta_2O_5. Other pegmatite contains manganocolumbite	Miles et al., 1945; Simpson, 1952; Witt, 1992
Holleton[(a)]				
Location	31°57'02"	119°01'04"	An albite pegmatite was found to contain tantalite and garnet	Simpson, 1952
Jimperding[(a)]				
Location	31°35'10"	116°21'29"	A single crystal of tapiolite found in alluvial gravel	Simpson, 1952
Kathleen Valley				
Prospect	27°31'52"	120°33'26"	Sn and Ta. Zoned and layered cassiterite-rich albitic pegmatite. Tantalite specimen assayed 60% Ta_2O_5 and 24% Nb_2O_5	Miles et al., 1945; Witt, 1992
Logans Find[(a)]				
Locality	31°21'10"	121°25'43"	Minor tantalite present in a quartz–lepidolite–muscovite–albite pegmatite	Simpson, 1952
Mellvile (Noongal)[(a)]				
Prospect	28°10'55"	116°45'16"	Ta, topaz, beryl, and emerald. Quartz–feldspar pegmatite, and quartz and porphyry veins. Pegmatite contains green beryl, and manganotantalite with assay values of 65% Ta_2O_5 and 19% Nb_2O_5	Miles et al., 1945
Mount Belches				
Prospect	31°26'05"	122°07'20"	See Eight Mile Dam	
Mount Dale				
Prospect	32°01'41"	116°21'32"	Small beryl-bearing, micaceous pegmatite in granite. Contains manganocolumbite and minor euxenite. Manganocolumbite assayed 64% Nb_2O_5 and 16% Ta_2O_5	Miles et al., 1945
Mount Day				
Prospect	32°08'53"	120°29'17"	Fractionated, subhorizontal pegmatite sheets containing columbite–tantalite and lepidolite. Grab and rock-chip assays of 30–390 ppm Ta, and <1250 ppm Nb	A10797; Witt, 1992
Mount Hope[(a)]				
Locality	32°11'32"	119°44'35"	Small, highly fractionated, west-trending pegmatite. Contains spodumene, manganotantalite, microlite, and rubellite tourmaline	Witt, 1992
Mount Marion				
Locality	31°04'41"	121°28'00"	Flat-lying pegmatite sheets. Several pegmatites exposed over 2.5 km. Contains spodumene and minor beryl, columbite–tantalite, and cassiterite	Witt, 1992
Mount Thirsty				
Locality	32°04'26"	121°39'47"	Zoned pegmatites in the area may be prospective for tantalum and tin	A 41242; Witt, 1992
Mundijong[(a)]				
Locality	32°17'43"	115°59'12"	Manganotantalite specimen probably collected near Mundijong	Simpson, 1952

Deposit/prospect/ locality	*Location Latitude (S)*	*Longitude (E)*	*Comments*	*Data source*
Native Dog Gully/Ross Find				
Locality	34°04'05"	116°00'40"	Area contains up to three discrete pegmatites	A14322; A17777; Blockley, 1980
Smithfield/Donovans Find/Paynes Shaft				
Prospect	34°03'25"	116°00'29"	Alluvial/eluvial (Sn, Ta). Maximum grades of 0.852 kg/m^3 SnO_2 and 0.022 kg/m^3 Ta_2O_5. Seven pegmatites exposed at Paynes Shaft. Maximum grades of 0.53 kg/m^3 SnO_2 and 0.01kg/m^3 Ta_2O_5	A1471; A1692; A14322; A17777; A28232; Blockley, 1980
Spargoville[(a)]				
Location	31°14'52"	121°28'10"	A specimen of manganotantalite was found in a feldspar vein about 4.8 km from Spargoville near the Norseman–Coolgardie road. The manganotantalite assayed 64% Ta_2O_5 and 20% Nb_2O_5. Total recorded tantalite–columbite production of 5.3 t	Simpson, 1952; Witt, 1990
Ubini[(a)]				
Prospect	30°56'27"	120°57'23"	Amblygonite-bearing quartz reef or pegmatite. Contains manganotantalite with 52–68% Ta_2O_5 and 14–31% Nb_2O_5,	Miles et al., 1945; Simpson, 1952
Victoria Rocks[(a)]				
Locality	31°18'32"	120°55'00"	Eluvial fragments of tantalite (assay values of 57–77% Ta_2O_5 and 8–27% Nb_2O_5) and manganocolumbite	Miles et al., 1945
Warda Warra				
Deposit	27°38'06"	117°07'41"	Alluvial/eluvial (Ta). Estimated reserves of 8559 m^3 containing 2.047 t of tantalite. Pegmatite contains tapiolite, microlite, columbite–tantalite, and simpsonite mineralization. Total recorded tantalite–columbite production of 10.6 t	A11882; Witt, 1990
Willow Springs				
Prospect	34°04'09"	115°56'51"	Alluvial/eluvial (Sn, Ta). Average analyses of 0.13% SnO_2 and 0.004% Ta_2O_5. Estimate of former mining is 0.85 t SnO_2 and 27 kg Ta_2O_5	A14322
Woljenup				
Locality	33°55'37"	116°03'57"	Deeply weathered regolith. Contains low-order tantalum values	A32846

NOTES: Sources of exploration data at the Department of Industry and Resources, Western Australia:
A45014 Mineral exploration report in the WAMEX database
S2304 Mineral site information in the MINEDEX database
Report summaries and other mineral information are available by accessing these databases at <http://www.doir.wa.gov.au>
(a) Position approximate
(b) Position doubtful

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This Bulletin on tantalum compiles much of the published and unpublished data on tantalum occurrences and prospectivity in the State. Tantalum most commonly occurs in rare-metal pegmatites found in many areas of Western Australia. The Greenbushes mine in the South West and the Wodgina mine in the Pilbara region are respectively the largest and second-largest tantalum operations in the world. Western Australia has many prospective targets for future development of tantalum resources such as the areas around Ravensthorpe, Binneringie, and Mount Deans in the south, and Arthur River and Wodgina in the north. A detailed study is included of the global tantalum industry in terms of tantalum manufacture, applications, marketing, and Western Australia's contribution to the global context.

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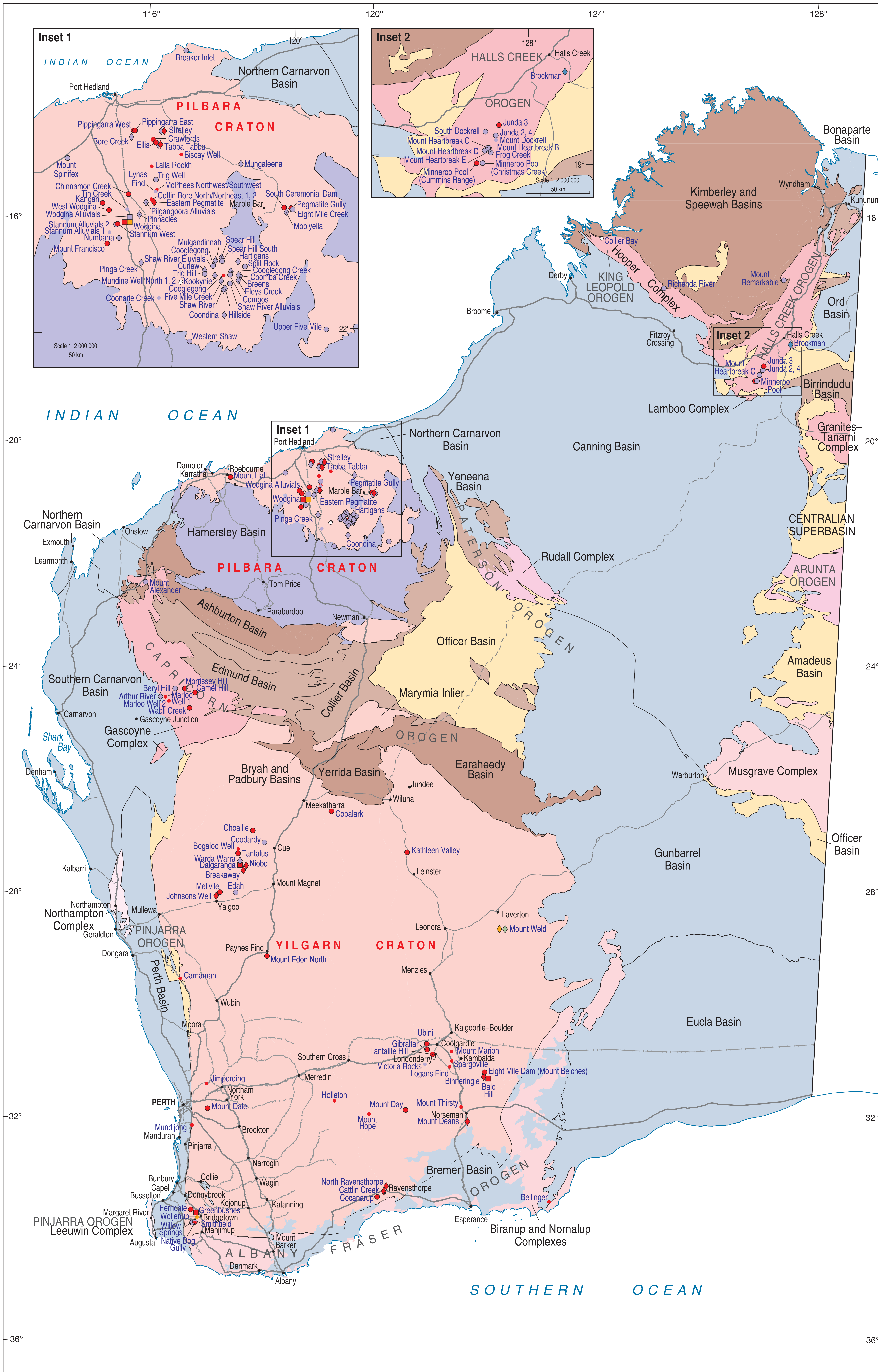
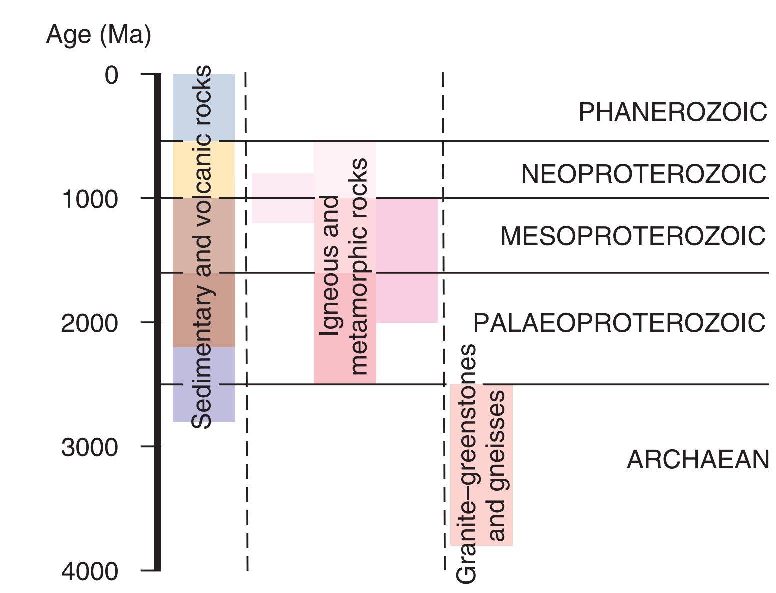
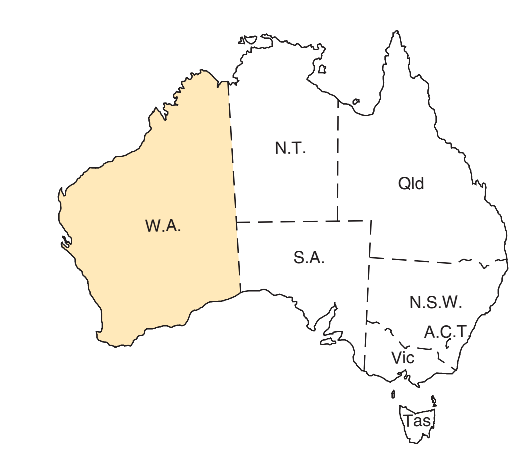


REFERENCE

Deposit style	Mine	Deposit	Prospect	Occurrence
Granitic rare-metal pegmatite	■	♦	●	•
Carbonatite		♦		
Subalkaline granite/syenite		♦		
Regolith				
Deeply weathered	■	♦		•
Placer	■	♦	●	•
Unknown				○



- Collie City or town
- Highway
- Major road
- Track
- Railway



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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
MINERAL RESOURCES BULLETIN 22, PLATE 1

TANTALUM OCCURRENCES IN WESTERN AUSTRALIA

SCALE 1: 5 000 000

0 50 100 150 200

Kilometres

Compiled by J. M. Fetherston
Geology by I. M. Tyler and R. M. Hocking, 2002, A revision of the tectonic units of Western Australia: Western Australia Geological Survey, Annual Review 2000–01, p. 33–44.
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