

Niobium–tantalum

April 2011

Definitions, mineralogy and deposits

Definitions and characteristics

Niobium (Nb) and tantalum (Ta) are transition metals with very similar physical and chemical properties, and are thus commonly grouped together (Table 1). Niobium was discovered in 1801 by Charles Hatchett, and was originally named 'columbium'; it was subsequently also recognised by a German chemist, Heinrich Rose, who named it 'niobium'. The names were used interchangeably for some time, before 'niobium' was finally accepted in 1949. Tantalum was discovered in 1802 by a Swedish scientist, Anders Ekeberg.

Niobium is a shiny, ductile metal with a white lustre. Naturally-occurring niobium consists almost exclusively of the isotope ^{93}Nb ; natural tantalum is mainly ^{181}Ta , with 0.012 per cent ^{180}Ta . A number of other radioactive isotopes of both elements have been synthesised.

The overall abundances of niobium and tantalum in the average continental crust are relatively low, niobium having an abundance of eight parts per million (ppm) and tantalum of 0.7 ppm (Rudnick and Gao, 2004). Compared to other metallic elements such as the light rare earths, niobium and tantalum are rather depleted in the continental crust. This can be attributed to the fact that much of the continental crust was formed at convergent margins above subduction zones, and that magmas formed in this setting are typically depleted in both niobium and tantalum.

Mineralogy

Niobium and tantalum do not occur naturally as free metals, but are essential components in a range of mineral species (Table 2). The majority of these are oxide minerals; silicates of niobium and tantalum do exist, but are relatively rare. Niobium and tantalum also substitute for major ions in a number of other minerals, in which they typically have low concentrations. The vast majority of the economically important species are oxides.

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	Niobium (Nb)	Tantalum (Ta)
Atomic number	41	73
Atomic weight	92.90638	180.9479
Density at 293 K (g/cm ³)	8.581	16.677
Melting point °C	2468	2996
Boiling point °C	4930	5425
Vickers hardness MPa	1320	873
Electrical resistivity (nano ohm-metres)	152 at 0°C	131 at 20°C
Crystal structure	Body centred cubic	Body centred cubic

Table 1 Selected properties of niobium and tantalum.

The columbite-tantalite mineral group (Figure 1) is the most common group of tantalum- and niobium-bearing minerals. Wodginite is also an important source of tantalum. The pyrochlore group (Figure 2) is of great economic importance, particularly for niobium. This group has a wide compositional range, including some species rich in both niobium and tantalum. Pyrochlore is typically found as a primary mineral in alkaline igneous rocks.



Figure 1 Dark coloured tantalite with pale coloured albite¹.

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Mineral name	Mineral group	Formula	Nb ₂ O ₅ (%)	Ta ₂ O ₅ (%)
Columbite	Columbite-tantalite	(Fe,Mn)(Nb,Ta) ₂ O ₆	78.72	n.a.
Tantalite	Columbite-tantalite	(Fe,Mn)(Ta,Nb) ₂ O ₆	n.a.	86.17
Pyrochlore	Pyrochlore	(Na,Ca) ₂ Nb ₂ O ₆ (O,OH,F)	75.12	n.a.
Microlite	Pyrochlore	(Na,Ca) ₂ Ta ₂ O ₆ (O,OH,F)	n.a.	83.53
Tapiolite	Tapiolite	(Fe,Mn)(Ta,Nb) ₂ O ₆	1.33	83.96
Ixiolite	Ixiolite	(Ta,Nb,Sn,Mn,Fe) ₄ O ₈	8.30	68.96
Wodginite	Wodginite	(Ta,Nb,Sn,Mn,Fe)O ₂	8.37	69.58
Loparite	Perovskite	(Ce,La,Na,Ca,Sr)(Ti,Nb)O ₃	16.15	n.a.
Lueshite	Perovskite	NaNbO ₃	81.09	n.a.
Euxenite	Euxenite	(Y,Ca,Ce,U,Th)(Nb,Ti,Ta) ₂ O ₆	47.43	22.53
Struverite	Rutile	(Ti,Ta,Fe)O ₂	11.32	37.65
Ilmenorutile	Rutile	Fe _x (Nb,Ta) _{2x} 4Ti _{1-x} O ₂	27.9	n.a.

Table 2 Selected niobium and tantalum minerals and indicative contents of Nb₂O₅ and Ta₂O₅.



Figure 2 Pyrochlore. Source: Rob Lavinsky (iRocks.com)².

Other, less common oxides of niobium and tantalum include tapiolite, ixiolite, and minerals of the perovskite group. Niobium and tantalum also substitute for major ions in some common oxide groups such as cassiterite, rutile, and ilmenite. Contents of niobium and tantalum in these minerals are rarely high enough to make them of economic interest. Similarly, niobium and tantalum occur as substitutes in a range of silicate minerals, typically those found in alkaline igneous rocks such as eudialyte (Na₄(Ca,Ce)₂(Fe⁺⁺,Mn,Y)ZrSi₈O₂₂(OH,Cl)₂).

² Image taken by Rob Lavinsky. Permission to use given by a creative commons licence (accessed 25/03/2011 at www.commonswiki.org). Attribution: Rob Lavinsky, iRocks.com (<http://www.irocks.com/>) – CC-BY-SA-3.0.

Deposits

Niobium and tantalum mineral deposits are most commonly associated with igneous rocks³, including granites, pegmatites⁴, syenites⁵ and carbonatites⁶. Some secondary deposits, where niobium- and tantalum-bearing minerals have been concentrated by weathering and sedimentary processes, are also known (see Table 3 and Figure 3 at the end of this section). In general, these secondary deposits occur in relatively close association with their primary sources, and so they are not considered separately in the descriptions below.

Primary Niobium and Tantalum deposits can be divided into three main types, on the basis of the igneous rocks with which they are associated (Küster, 2009):

1. Carbonatites and associated rocks
2. Alkaline to peralkaline granites and syenites
3. Granites and pegmatites of the LCT family (enriched in lithium (Li), caesium (Cs), tantalum) (Černý and Ercit, 2005).

Moderately high contents of niobium and tantalum may be found in some granites and pegmatites that do not fall into the categories given above, but economic examples are not known.

³ Igneous rocks: rocks with a crystalline texture that crystallised from molten rock (magma).

⁴ Pegmatites: very coarse-grained igneous rocks.

⁵ Syenites: coarse-grained igneous rocks that are composed largely of the potassium- and/or sodium-rich mineral alkali feldspar.

⁶ Carbonatites: igneous rocks consisting of more than 50 per cent primary carbonate minerals.

Carbonatites and associated rocks

Carbonatites are igneous rocks that consist of more than 50 per cent primary carbonate minerals. They are almost exclusively found in areas of continental extension and rifting⁷, and their source magmas are thought to be derived directly from the mantle with very little crustal influence. Carbonatites are most commonly found as dykes, sills and small plugs (less than one kilometre in diameter), more rarely occurring as large plutons or as extrusive⁸ volcanic sequences. They rarely occur in isolation, being more commonly associated with alkaline⁹ silicate rocks, either nepheline syenite and other feldspathoid-bearing¹⁰ igneous rocks, or mafic¹¹ to ultramafic¹² alkaline rocks (Woolley and Kjarsgaard, 2008). Many carbonatite bodies are surrounded by a metasomatised¹³ or 'fenitised' zone, typically rich in sodium (Na) and/or potassium (K), formed through alteration of the country rocks by fluids derived from the carbonatite. Some carbonatite bodies are considered to be carbohydrothermal¹⁴—formed from carbon dioxide-rich and water-rich fluids rather than magmas.

Carbonatites are typically enriched in a range of elements, including the rare earth elements (REE), barium (Ba), strontium (Sr), fluorine (F), phosphorus (P), niobium (Nb), zirconium (Zr), uranium (U) and thorium (Th). Niobium is preferentially enriched over tantalum in carbon dioxide-rich melts, and so carbonatites do not generally have high tantalum contents (Möller, 1989). Common niobium-bearing minerals found in carbonatites include members of the perovskite and pyrochlore mineral groups, as well as niobium-rich silicates such as titanite (Mitchell, 2005).

In general, bulk rock niobium contents for carbonatite bodies are moderately high (commonly 0.01–0.1 per cent, rarely up to 1.0 per cent), but not ore-grade. However, magmatic differentiation¹⁵ processes such as crystal settling may concentrate niobium-bearing minerals such as pyrochlore. Weathering processes¹⁶ may also concentrate

these minerals in the shallow subsurface. Late-stage veins and areas of metasomatism, formed through carbohydrothermal activity, are a third potential source of niobium mineralisation.

Much of the world's niobium supply comes from Brazil, where the main niobium deposits occur in alkaline ultramafic-carbonatite complexes of the Late Cretaceous¹⁷ Alto Paranaíba igneous province, intruded into Neoproterozoic¹⁸ metasedimentary rocks. The largest currently worked niobium deposit is at Araxá, and is owned and exploited by the Companhia Brasileira de Metalurgia e Mineração (CBMM). A second major niobium mine, at Catalão, is operated by Anglo American. These deposits are hosted in rather unusual intrusions consisting of carbonatite- and phoscorite¹⁹-series rocks with no associated syenites. In both deposits, pyrochlore is the main niobium ore mineral. The Araxá deposit lies within the Barreiro Carbonatite Complex, a roughly circular intrusion approximately 4.5 kilometre in diameter (Nasraoui and Waerenborgh, 2001), dominated by dolomite carbonatite with subordinate calcite carbonatite, glimmerite²⁰ and phoscorite. The central part of the intrusion has been weathered under tropical conditions to form a thick (>200 metres), lateritic²¹ cover in which pyrochlore has become concentrated at a reported mean grade of 2.5 per cent niobium oxide, and which is exploited by open-pit mining. The country rocks to the carbonatite have been metasomatised in an aureole²² up to 2.5 kilometre wide (Nasraoui and Waerenborgh, 2001). The main worked deposit at Catalão is in the Catalão I alkaline-carbonatite complex, but a similar deposit occurs in the nearby Catalão II complex. Catalão I is a steep-sided, zoned intrusive body with a diameter of approximately six kilometres at the surface. It is dominated by glimmerite (phlogopite) at the margins of the complex, with sheets and plugs of dolomite-carbonatite and phoscorite-series rocks that become increasingly common towards the centre of the complex (Cordeiro *et al.*, 2010). As at Araxá, the mined deposit is in the weathered lateritic zone above the centre of the complex.

The largest active niobium mine outside Brazil is the Niobec mine in Quebec, Canada, operated by the Iamgold

⁷ Continental rifting: the gradual break-up of a continent under extension, as is occurring at the present day in East Africa.

⁸ Extrusive: extrusive volcanic rocks are formed by eruption of magma on to the Earth's surface.

⁹ Alkaline rocks: igneous rocks that are rich in sodium and potassium, and contain certain characteristic minerals.

¹⁰ Feldspathoids: a group of light-coloured minerals that have relatively low silica contents.

¹¹ Mafic rock: a rock containing abundant dark-coloured minerals that are rich in magnesium and/or iron.

¹² Ultramafic: a rock almost entirely made up of dark-coloured minerals that are rich in magnesium and/or iron.

¹³ Metasomatised: having undergone metasomatism, chemical alteration of a rock by the action of fluids.

¹⁴ Carbohydrothermal: formed from hot carbon dioxide-rich and water-rich fluids.

¹⁵ Magmatic differentiation: processes by which certain elements or minerals are concentrated either in the crystalline rock or in the residual molten magma.

¹⁶ Weathering processes: processes by which rocks are altered at the earth's surface.

¹⁷ Late Cretaceous: a unit of geological time between 99 to 65 million years ago.

¹⁸ Neoproterozoic: a unit of geological time between 1000 to 542 million years ago.

¹⁹ Phoscorite: A magnetite, olivine, apatite rock, usually associated with carbonatites.

²⁰ Glimmerite: An ultramafic rock consisting almost entirely of mica, either biotite or phlogopite. Can also be called biotitite or phlogopitite as appropriate.

²¹ Lateritic: relating to laterite, a residual deposit rich in iron and aluminium resulting from weathering under tropical conditions.

²² Aureole: an area around a body of igneous rock in which the host rocks have been altered by the effects of increased temperature, pressure or fluid flow.

Corporation. This mine lies in the southern part of the Neoproterozoic-age Saint-Honoré carbonatite complex, which has an elliptical shape and is approximately four kilometres across at the surface. It consists of a series of crescentic lenses of carbonatite, younging inwards from calcite carbonatite through dolomite carbonatite to ferrocarnatite (Belzile, 2009). The carbonatite body is surrounded by a ring of syenites and diorites, and is almost entirely covered by Palaeozoic²³ limestones. Pyrochlore is the main niobium mineral in the Saint-Honoré complex. It is disseminated throughout the carbonatite, but is particularly abundant in mineralised lenses that are 50–150 metres wide and up to approximately 750 metres long, with grades of 0.44–0.51 per cent niobium oxide (Belzile, 2009). These mineralised zones occur at depths of over 100 metres beneath the surface, and the Niobec mine is the only underground niobium mine in the world. On the same structural lineament, the nearby Crevier syenite-carbonatite complex contains a niobium-tantalum deposit which is currently being evaluated.

Numerous other carbonatite-hosted niobium deposits are known across the world, but are not currently being exploited. The most significant of these are the Tomtor deposit in Siberia, Russia and the Morro dos Seis Lagos deposit in Brazil (Pollard, 1995). The Neoproterozoic-age Tomtor alkaline complex comprises an outer ring of nepheline-syenites, with a central stock²⁴ of carbonatite, having a surface area of approximately 12 square kilometres (Kravchenko and Pokrovsky, 1995). Pyrochlore is disseminated throughout the carbonatite, but is particularly concentrated in two ore horizons. The lower ore horizon, which is up to 300 metres thick, represents the weathered and altered top to the carbonatite body, whilst the upper ore horizon is a buried placer deposit²⁵ formed in an ancient lake, associated with Permian²⁶ sedimentary rocks. The upper ore horizon contains more than 12 per cent niobium (Kravchenko and Pokrovsky, 1995). The Morro dos Seis Lagos deposit is poorly known, to the extent that even its age is uncertain (Berger *et al.*, 2009), but it is thought to represent the largest single niobium deposit in the world with 2897 million tonnes niobium (Pollard, 1995).

A total of 58 carbonatite bodies containing niobium and rare earth element mineral deposits have been recorded in published work (Berger *et al.*, 2009) and other such deposits may remain to be found. The smaller deposits include

²³ Palaeozoic: a unit of geological time between 542 and 251 million years ago.

²⁴ Stock: a small body of igneous rock, emplaced beneath the Earth's surface, usually cylindrical with steep margins.

²⁵ Placer deposit: a concentration of heavy minerals transported and deposited by rivers and/or coastal processes.

²⁶ Permian: a unit of geological time between 299 and 251 million years ago.

well-studied examples from Lueshe (Democratic Republic of Congo), Oka (Quebec, Canada), and Söklí (Finland). The Lueshe syenite-carbonatite complex, which is Cambrian²⁷ in age, has a central core of syenite some 800 metres in diameter, bordered by a ring dyke of calcite carbonatite and dolomite carbonatite (Nasraoui and Bilal, 2000). Intense weathering of the carbonatites has formed a laterite horizon which is enriched in pyrochlore, and has been mined for niobium. The Cretaceous²⁸ Oka carbonatite complex is an elongate pluton, about seven kilometres long, comprising carbonatites and feldspathoid-bearing silicate rocks. It includes three separate niobium-mineralised deposits containing minerals of the perovskite and pyrochlore groups (Zurevinski and Mitchell, 2004). The Söklí carbonatite-phoscorite complex is Devonian²⁹ in age, with an area of about 20 square kilometres, and comprises metasomatised ultramafic rocks, carbonatites and phoscorites, with abundant pyrochlore in the younger units of the complex (Lee *et al.*, 2006). The major Bayan Obo rare earth element deposit in China, which is also enriched in niobium, is associated with carbonatite magmatism and may have been formed by the interaction of carbonatite-derived fluids and sedimentary host rocks (Yang *et al.*, 2009).

Alkaline to peralkaline granites and syenites

The alkaline igneous rocks are classified, on the basis of mineralogy, as those rocks containing certain sodium- or potassium-rich minerals (feldspathoids, alkali amphiboles, or alkali pyroxenes). Peralkaline rocks are a subset in which the molecular amount of Na₂O + K₂O exceeds Al₂O₃³⁰. Alkaline rocks are most commonly found in intra-plate settings such as zones of continental rifting, but they may also be formed in post-collisional³¹ to post-orogenic³² environments. The most evolved alkaline igneous rocks, such as alkali granites and syenites, are characterised by high contents of iron (Fe), fluorine, niobium, zirconium, rubidium (Rb), uranium, thorium and rare earth elements but low niobium and tantalum (Pollard, 1989, Küster, 2009). Mineral deposits in alkaline igneous rocks typically contain high contents of zirconium, yttrium (Y), niobium and the rare earth elements, but are less commonly enriched in tantalum.

Several factors contribute to the enrichment of High Field Strength Elements³³ (HFSE), such as niobium and zircon-

²⁷ Cambrian: a unit of geological time between 542 and 488 million years ago.

²⁸ Cretaceous: a unit of geological time between 145 and 65 million years ago.

²⁹ Devonian: a unit of geological time between 416 and 359 million years ago.

³⁰ Na₂O, K₂O and Al₂O₃: sodium oxide, potassium oxide and aluminium oxide.

³¹ Post-collisional: post-dating the peak of continental collision.

³² Post-orogenic: post-dating all tectonic processes associated with a continental collision event (orogeny).

³³ High field strength elements: Elements of high valency (able to combine with many other elements to form compounds) that are incompatible (see footnote 34).

niom, in alkaline igneous rocks such as alkaline granites and syenites. Alkaline magmas are most commonly considered to be derived from the enriched sub-continental lithospheric³⁴ mantle, and are enriched in the HFSE from their formation. The HFSE are incompatible³⁵ and thus they become enriched in the most evolved, granitic and syenitic magmas; in some localities, ore minerals are found disseminated throughout highly evolved granites and syenites. Further concentration can occur because the HFSE typically form relatively dense minerals, which may be accumulated through crystal settling into layers. The most famous example of a niobium deposit formed in this way is in the Ilímaussaq Complex of south-west Greenland. However, many mineralised deposits within alkaline rocks, such as the Motzfeldt deposit in Greenland, have undergone further concentration of elements such as the HFSE and REE through hydrothermal³⁶ processes (Salvi and Williams-Jones, 2005). The HFSE and REE appear to be highly mobile in fluids associated with peralkaline magmas that are enriched in fluorine, chlorine (Cl) and/or carbon dioxide (Goodenough *et al.*, 2000, Salvi and Williams-Jones, 2005).

At the time of writing, there are few niobium or tantalum mines operating in alkaline granite and syenite complexes, although exploration is under way in some areas. One major area of interest lies in the Mesoproterozoic³⁷ Gardar Igneous Province in south-west Greenland, including the Ilímaussaq and Motzfeldt complexes. The Ilímaussaq Complex is elliptical, 8 x 17 kilometres at the surface, and comprises a range of mineralogically unique syenites and alkaline granites which are spectacularly layered in places (Larsen and Sorensen, 1987). The main mineral deposits occur in a unit of layered syenites known as kakortokites, which contains twenty-nine separate layers that are rich in eudialyte, with high contents of zirconium, yttrium, niobium and the REE. The average grade of niobium in these layers is 0.1 weight per cent niobium oxide (Salvi and Williams-Jones, 2005). In the Kvanefjeld area of the Ilímaussaq Complex, hydrothermal veins in the syenites and their country rocks contain significant uranium-niobium mineralisation. Zones of hydrothermally altered syenite also host the niobium-tantalum-REE pyrochlore mineralisation in the Motzfeldt intrusion (Steenfelt, 1991) which is the subject of an ongoing exploration programme.

³⁴ Lithospheric: the lithosphere is the outer, rigid layer of the Earth, including both the Earth's crust and the uppermost part of the mantle.

³⁵ Incompatible elements: are those that are concentrated into molten magmas, rather than into early-forming crystals of solid minerals.

³⁶ Hydrothermal: formed from hot water-rich fluids.

³⁷ Mesoproterozoic: a unit of geological time between 1600 and 1000 million years ago.

In Russia's Kola Peninsula, the Devonian-age Lovozero syenite massif contains layered syenites with layers that are rich in eudialyte, loparite and apatite. Loparite has been mined on and off for many years, and the loparite concentrates have average grades of eight weight per cent niobium oxide and 0.7 weight per cent tantalum oxide (Salvi and Williams-Jones, 2005). The Mesoproterozoic-age Pilanesberg Complex of South Africa is another large (> 500 square kilometres) alkaline complex with eudialyte-rich syenites that are enriched in zirconium, niobium and the REE.

In eastern Canada, the Strange Lake peralkaline granite pluton, which is Mesoproterozoic in age, outcrops over an area of about 36 square kilometres. It has a central ore zone where the granite has undergone extensive haematisation³⁸ and calcium metasomatism, producing a range of secondary HFSE-bearing minerals, including gittinsite³⁹ and pyrochlore. Ore from this zone has an average grade of 0.56 weight per cent niobium oxide (Salvi and Williams-Jones, 2005, Salvi and Williams-Jones, 2006). In Canada's Northwest Territories, the Palaeoproterozoic Blatchford Lake igneous complex comprises syenites and peralkaline granites with a number of hydrothermally altered mineralised zones, known as the Thor Lake deposits. These deposits are enriched in beryllium (Be), yttrium, REE, niobium, tantalum and zirconium, with columbite-tantalite minerals hosting the majority of the niobium and tantalum, and average grades up to 0.4 weight per cent niobium (Salvi and Williams-Jones, 2005). The Thor Lake deposits are currently owned by Avalon Rare Metals Inc, which intends to develop them for REE, niobium and tantalum.

In Mongolia, the Devonian-age Khaldzan-Buregtey zirconium-niobium-REE deposit is formed by the hydrothermally altered late phase intrusions of a peralkaline granite massif (Kovalenko *et al.*, 1995). Pyrochlore is the main niobium ore mineral. In Malawi, exploration is ongoing at the Kanyika niobium-tantalum deposit, which comprises an elongate body of nepheline syenite over 3.5 kilometres long with numerous mineralised, pyrochlore-bearing veins (BGS, 2009). In Saudi Arabia, the Ghurayyah alkaline granite stock is about 800 metres in surface diameter and contains disseminated tantalum and niobium ore minerals, chiefly columbite-tantalite and pyrochlore. The distribution of these ore minerals appears to be remarkably consistent throughout the granite (Küster, 2009). In Brazil, niobium and tantalum are extracted along with tin from a Palaeoproterozoic-age albite-rich peralkaline granite at

³⁸ Haematisation: alteration associated with the formation of the iron oxide mineral, haematite.

³⁹ Gittinsite: A calcium-zirconium-bearing silicate mineral.

the Pitinga mine (Bastos-Neto *et al.*, 2009). Alkaline to peralkaline intrusions with the potential for niobium and/or tantalum deposits occur in many other countries, including Morocco, Nigeria, and Namibia.

Granites and pegmatites of the LCT family (enriched in lithium, caesium, tantalum)

Granites and pegmatites of the LCT family are typically peraluminous⁴⁰ and enriched in lithium, rubidium, caesium, beryllium, tin (Sn), tantalum and niobium (tantalum greater than niobium) (Černý and Ercit, 2005). These magmas are formed by melting of pre-existing crustal rocks, and were most commonly emplaced as post-orogenic plutons in zones of continental collision. Granites and pegmatites of this type are the main hosts for tantalum deposits across the world. These intrusions typically take the form of a large peraluminous leucogranitic⁴¹ pluton surrounded by a halo of pegmatites, with the most mineralised pegmatites at the greatest distance from the granite (Černý, 1989), although in some areas swarms of pegmatites are not associated with exposed granitic plutons.

The granite bodies contain minerals such as biotite, muscovite, topaz and tourmaline, and are typically rather heterogeneous, showing extensive albitisation⁴² and alteration by late-stage fluids. These granites may contain disseminated tantalum ore minerals, particularly concentrated in the uppermost parts of the granitic body (Linnen and Cuney, 2005).

Many of the largest tantalum deposits occur in pegmatite swarms. LCT pegmatites can be divided into five types: the beryl type; the complex (spodumene-petalite-amblygonite) type; the complex lepidolite type; the albite-spodumene type; and the albite type (Černý, 1989). Many of the pegmatites falling into the first three types are zoned. All types can contain a range of tantalum minerals, of which the most important are generally columbite-tantalite, microlite, ixiolite and wodginite. Tantalum-rich cassiterite (tin oxide) is also an important ore mineral in some bodies. Many of the pegmatites have been highly affected by late-stage alteration, such as kaolinisation⁴³.

In recent years, much of the world's production of tantalum has come from the Greenbushes and Wodgina mines in Australia, although production from these mines ceased

between 2008 and 2011. Both mines are owned by Global Advanced Metals (previously Talison). The Greenbushes mine in south-western Australia is hosted in a giant (greater than three kilometre long) syn-tectonic⁴⁴, zoned, complex-type pegmatite body of Archaean⁴⁵ age, which contains large resources of both tantalum and lithium, associated with tin mineralisation. This pegmatite does not appear to be genetically associated with a larger granitic body (Partington *et al.*, 1995). Three phases of tantalum mineralisation are recorded within this pegmatite: early-formed minerals such as wodginite and ixiolite, which form inclusions in cassiterite and tourmaline; tantalites and tapiolites in fractures within early silicate phases; and later hydrothermal mineralisation, where microlite is the main tantalum mineral (Partington *et al.*, 1995). The Greenbushes pegmatite has been exploited by both open pit and underground mining. In north-western Australia, a large number of pegmatite swarms occur within the Archaean rocks of the Pilbara Craton, and many of these include some tantalum-mineralised examples. The most important area here is the Wodgina pegmatite district, which includes the Wodgina Main Lode and Mount Cassiterite tantalum-mineralised pegmatites. The Wodgina Main Lode is a dyke-like pegmatite about one kilometre long, of albite-type, with manganese-rich tantalite as the main tantalum mineral, together with some manganese-rich columbite and wodginite. At Mount Cassiterite the deposit is formed by a series of pegmatite sheets of albite-spodumene type, and wodginite is the main tantalum mineral (Sweetapple and Collins, 2002). Tantalum from these pegmatites is extracted by open pit mining.

An Archaean pegmatite body also forms the host for the tantalum mineralisation at Tanco, in Manitoba, Canada, owned by Cabot Corporation. It is part of the rare-metal bearing Bernic Lake pegmatite group, which intrudes metavolcanic⁴⁶ Archaean rocks. The Tanco pegmatite forms a shallowly dipping sheet, up to about 100 metres thick and 1600 metres along strike, which is exploited in a room-and-pillar underground mine. It is of the complex pegmatite type, and is strongly zoned; tantalum ore minerals are found throughout, though concentrated at higher grade in certain zones. A wide range of tantalum minerals occur (14 in all) and they are generally fine-grained, meaning that processing of Tanco ore is rather difficult (Černý, 1989). Caesium and lithium are also produced from the Tanco pegmatite. In addition, numerous other tantalum-mineralised pegmatites are known from the Superior

⁴⁰ Peraluminous: a chemical term used for rocks in which the total molecular (calcium oxide + sodium oxide + potassium oxide) is less than molecular aluminium oxide.

⁴¹ Leucogranitic: a light-coloured, silica-rich type of granite.

⁴² Albitisation: alteration by fluids to produce the sodium-rich mineral, albite, a type of feldspar.

⁴³ Kaolinisation: alteration of rocks to produce kaolin, also known as china clay.

⁴⁴ Syn-tectonic: formed during an episode of tectonic activity and deformation of the Earth's crust, usually an episode of continental collision.

⁴⁵ Archaean: a unit of geological time between 3800 and 2500 million years ago.

⁴⁶ Metavolcanic: metamorphosed volcanic rocks.

Province of Ontario and Manitoba (Selway *et al.*, 2005). In Brazil, a large (about one kilometre long), zoned, Proterozoic⁴⁷ pegmatite body of albite-spodumene type is mined for tantalum, niobium and lithium at the Volta Grande mine at Nazareno, in the Minas Gerais district (Lagache and Quemeneur, 1997).

In Mozambique, the Alto Ligonha Pegmatite Province contains numerous mineralised pegmatites which have been mined since 1926, with tantalum mining and exploration currently focused in the zoned Marropino and Morrua pegmatites, owned by Noventa Ltd. These pegmatites are intruded into the Proterozoic rocks of the Nampula Sub-province, and they are considered to be Ordovician⁴⁸ in age (Graupner *et al.*, 2010). Numerous examples of tantalum-mineralised granites and pegmatites are also found in

North Africa, intruded into the Neoproterozoic rocks of the Arabian-Nubian Shield (Küster, 2009). These include the Kenticha pegmatite field in Ethiopia, the Majahayan pegmatites of Somalia, and the Abu Dabbab and Nuweibi granites in Egypt. At Kenticha, the pegmatite field as a whole has an area of approximately 2500 square kilometres, but tantalum mining is focused on the Main Kenticha Pegmatite, a Cambrian-age dyke-like zoned pegmatite of complex-spodumene type which is mined for columbite-tantalite minerals (Küster, 2009). In Egypt, the Abu Dabbab and Nuweibi prospects are currently being developed towards production. These deposits are unusual in that the mineralisation is found in stock-like granite intrusions, rather than in pegmatites. Columbite-tantalite minerals are disseminated throughout these intrusions, and although the granites show significant evidence of later metasomatic alteration, the tantalum minerals are considered to be magmatic in origin (Küster, 2009).

⁴⁷ Proterozoic: a unit of geological time between 2500 and 542 million years ago.

⁴⁸ Ordovician: a unit of geological time between 488 and 443 million years ago.

Deposit type	Brief description	Typical grades and tonnage	Major examples
Carbonatite-hosted primary deposits	Niobium deposits found within carbonatitic igneous rocks in alkaline igneous provinces	Niobec, proven & probable reserves: 23.5 million tonnes at 0.59% Nb ₂ O ₅	Niobec, Canada; Oka, Canada
Carbonatite-sourced secondary deposits	Zones of intense weathering or sedimentary successions above carbonatite intrusions in which niobium ore minerals are concentrated	< 1000 million tonnes at up to 3% Nb ₂ O ₅ in lateritic deposits. Up to 12% Nb ₂ O ₅ in placer deposit at Tomtor, tonnage not known	Araxá and Catalão, Brazil; Tomtor, Russia; Lueshe, Democratic Republic of Congo
Alkaline granite and syenite	Niobium and lesser tantalum deposits associated with silicic alkaline igneous rocks. Ore minerals may be concentrated by magmatic or hydrothermal processes	Generally < 100 million tonnes, at grades of 0.1 to 1% Nb ₂ O ₅ and < 0.1% Ta ₂ O ₅	Motzfeldt and Ilímaussaq, Greenland; Lovozero, Russia; Thor Lake and Strange Lake, Canada; Pitinga, Brazil; Ghurayyah, Saudi Arabia; Kanyika, Malawi
LCT-type granite	Tantalum and lesser niobium deposits associated with peraluminous leucogranitic plutons, which are often hydrothermally altered	Generally < 100 million tonnes, at grades of < 0.05% Ta ₂ O ₅	Abu Dabbab and Nuweibi, Egypt; Yichun, China
LCT-type pegmatite	Tantalum and lesser niobium deposits associated with pegmatites of LCT (Li-Cs-Ta-enriched) type	Generally < 100 million tonnes, at grades of < 0.05% Ta ₂ O ₅	Greenbushes and Wodgina, Australia; Tanco, Canada; Volta Grande, Brazil; Kenticha, Ethiopia; Morrua & Marropino, Mozambique

Table 3 Key characteristics and examples of the major types of niobium and tantalum deposits (grades and tonnages are very variable between deposits and figures given are indicative only).

Niobium-tantalum

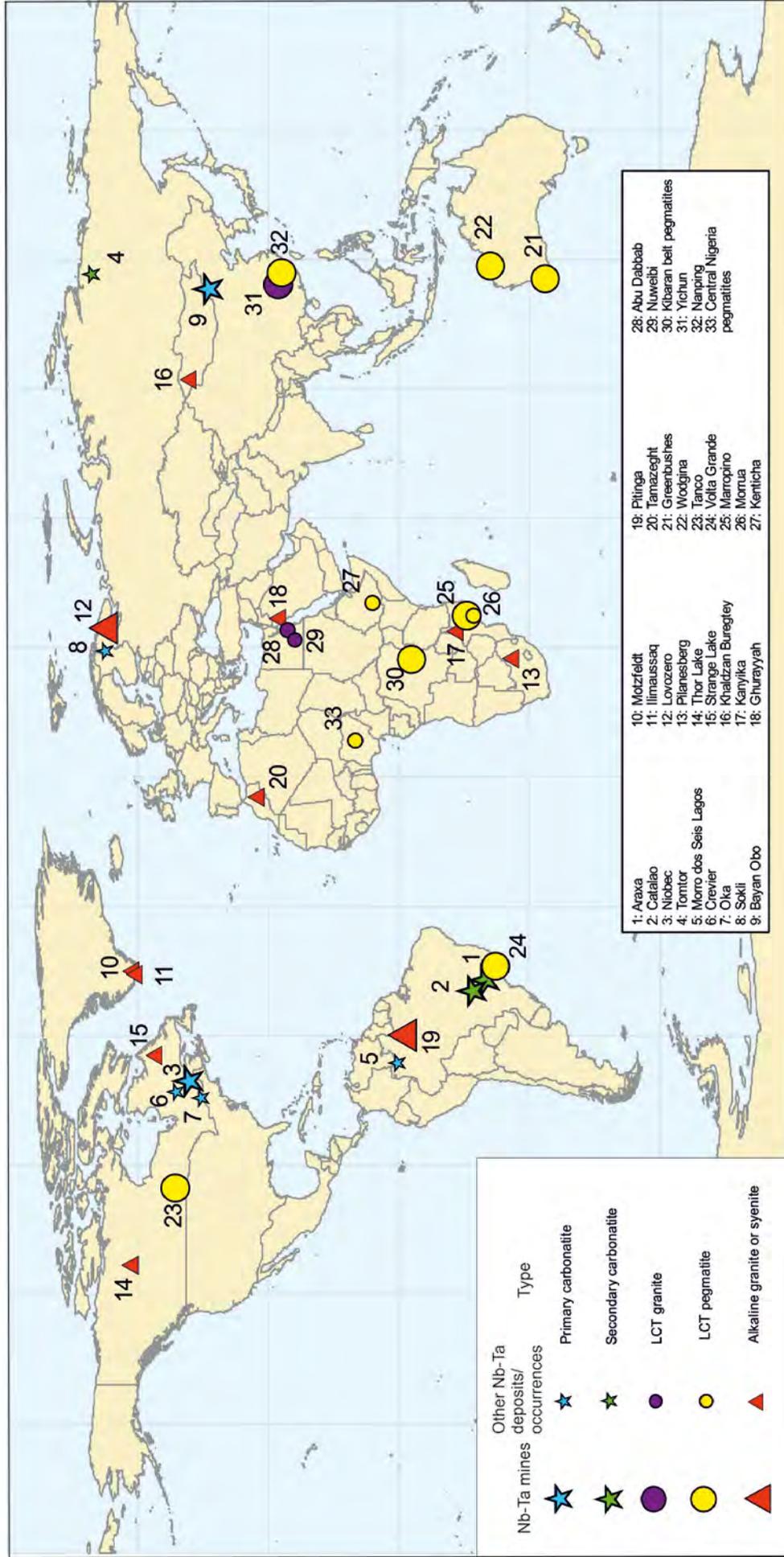


Figure 3 Map showing the global distribution of niobium and tantalum mines, deposits and major occurrences.

In Central Africa, a zone of Neoproterozoic-age tantalum-mineralised pegmatites cuts the Mesoproterozoic Kibaran belt which extends through Burundi, Rwanda, Uganda and the Democratic Republic of Congo (Romer and Lehmann, 1995). Columbite-tantalite minerals are mined both from deeply weathered pegmatites and from secondary placer deposits derived from the pegmatites.

Several regions of China have tantalum-mineralised granites and pegmatites. The most well known is the Yichun deposit, which is hosted in a small (less than 10 square kilometres) granitic batholith of Jurassic age. The uppermost part of this batholith is a highly fractionated topaz-lepidolite granite, which contains tantalum mineralisation in the form of disseminated columbite-tantalite, tantalum-rich cassiterite, and minor microlite (Yin *et al.*, 1995). Elsewhere in China, the Altai pegmatites (north-western China) and the Nanping pegmatites (south-eastern China) have been mined for columbite-tantalite in the past. In Malaysia and south-western Thailand, tin is produced from weathered tin-mineralised granites and pegmatites, and from secondary placer deposits. The tin slags are being reprocessed to produce tantalum.

Extraction methods and processing

Extraction

The mining methods employed to extract niobium and tantalum are similar to other metals of comparable occurrence. Factors that dictate the selection of mining methods include: the physical and chemical properties of the ore mineral; the tonnage and grade; and the shape, geometry and depth of the orebody. The most common methods of extraction are surface (or open-pit) and sub-surface (or underground) mining, or a combination of both. Significant amounts of niobium and tantalum are also extracted by artisanal and small scale mining (ASM).

Surface mining

Massive, or steeply-dipping, low-grade near-surface ore bodies are amenable to open-pit mining techniques. Open-pit methods commonly involve removing overburden, digging or blasting the ore, followed by removal of the ore by truck or conveyor belt for stockpiling prior to processing. Open-pit mining may reach depths of several hundred metres but seldom exceeds 100 metres. Heavily weathered ore bodies, such as the Araxá carbonatite deposit in Brazil, are also mined using open-pit methods.

Land-based placer deposits are amenable to strip mining involving scrapers, bulldozers and loaders. Placer deposits can be poorly consolidated, and only require drilling and

blasting where materials have become cemented. For example, tin-tantalum placers in Malaysia are mined using simple stripping methods, whilst hard-rock surface operations, such as Wodgina Mine, are mined using drilling and blasting techniques.

Capital and operating costs for open-pit techniques are far less than those for underground operations.

Underground mining

Underground mining methods are usually employed when surface methods are, or become prohibitively expensive, for example if the deposit becomes too deep. Another major factor in the decision to use underground methods is the waste to ore ratio, or strip ratio. Once the ratio becomes large, open-pit mining methods become uneconomic.

Underground operations commonly require extensive mine development including shaft sinking, de-watering, ventilation, geo-technical support and ore handling. Room and pillar is an underground mining technique where mining progresses in a horizontal direction by developing numerous stopes⁴⁹, or rooms, leaving pillars of material for roof support. Ore is blasted and then transported by rail, conveyor or dump truck to the processing plant. Room and pillar mining methods were used at the Tanco pegmatite in Manitoba, Canada. The mine is located under Bernic Lake and is accessed via a 60-metre shaft and via a 20-degree decline⁵⁰ from the surface (Cabot, 2001).

By-product production

Niobium and tantalum can also be extracted as a by-product of tin smelter waste. Niobium produced in this way accounts for less than two per cent of total global niobium production. However, the percentage is much higher for tantalum at around 14 per cent. Tantalum is extracted from cassiterite⁵¹ placer middlings⁵² using shaking tables, and magnetic⁵³ and electrostatic⁵⁴ separation methods. Tin smelter waste typically contains eight to 10 per cent tantalum oxide, although exceptionally this may rise to 30 per cent. Low-grade smelter wastes can be upgraded by electrothermic reduction⁵⁵ yielding a synthetic concentrate with up to 50 per cent tantalum and niobium oxides (Roethe, 1989).

⁴⁹ Stope: the void created by extracting the ore.

⁵⁰ Decline: a mine entrance which is neither horizontal nor vertical; often it takes the form of a spiral ramp.

⁵¹ Cassiterite: tin oxide ore mineral, SnO₂.

⁵² Middlings: particles of intermediate grade and size.

⁵³ Magnetic separation: the selective sorting of magnetically susceptible ore minerals using magnetic force.

⁵⁴ Electrostatic separation: the selective sorting of ore minerals using an electric field.

⁵⁵ Electrothermic reduction: a reduction reaction performed in an electric arc furnace, utilising calcium oxide, iron oxide and carbon as reducing agents.

Niobium-tantalum

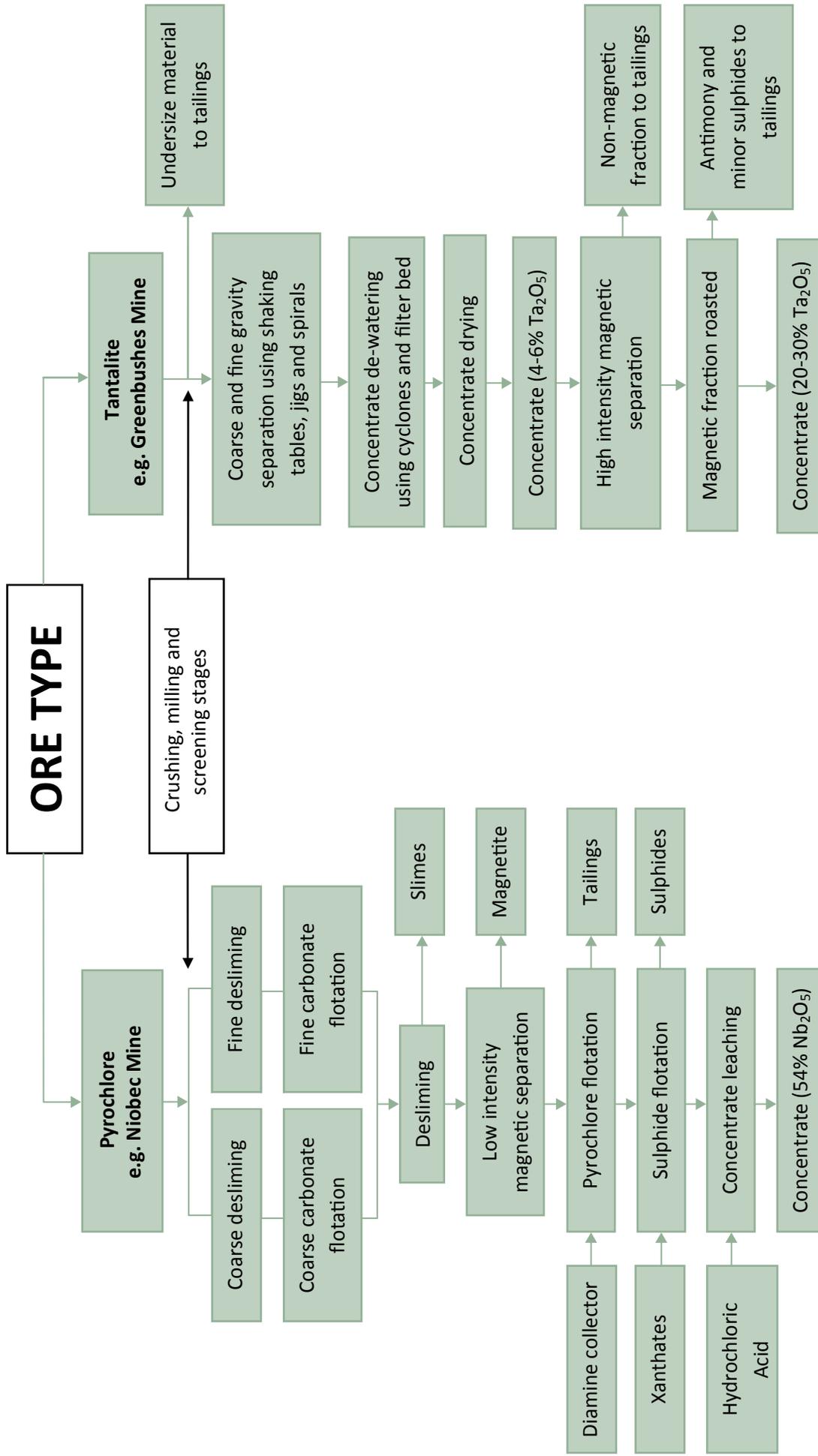


Figure 4 Generalised beneficiation flow diagrams, based upon the Niobec and Greenbushes operations.

Processing

After mining the ores are processed to increase their niobium and tantalum contents. Initial concentration is normally undertaken at, or close to, the mine site and involves crushing the ore followed by separation of niobium and tantalum ore from gangue⁵⁶ material, using a combination of physical and chemical methods. Although niobium and tantalum are geochemically similar each requires a different processing route.

Ore beneficiation

Niobium ore is first crushed in jaw, cone or impact crushers and milled in rod or ball mills operating in closed circuits with vibrating screens and screw classifiers⁵⁷ to liberate niobium mineral particles. The slurry containing niobium and waste rock is further concentrated to around 54 per cent niobium oxide using a number of methods in multiple stages: gravity separation⁵⁸, froth flotation⁵⁹, magnetic and electrostatic separation, and acid leaching⁶⁰ may be used, depending on the physical and chemical characteristics of the ore.

At the Niobec operation in Canada niobium ore is screened and classified, after which the resultant slurry is sent for desliming⁶¹. Carbonate material is removed by two stages of froth flotation, followed by an additional desliming stage. Magnetite is removed from the slurry, by low intensity magnetic separation, and sent to waste. The sought-after pyrochlore is collected from the slurry by froth flotation using diamine collectors⁶². A final stage of froth flotation is used to remove sulphides, such as pyrite. Residual impurities are leached by hydrochloric acid, leaving a final concentrate that contains around 54 per cent niobium oxide (Figure 4) (Iamgold, 2009).

Tantalum ores are initially treated in a similar manner to niobium ores; they are crushed, milled and screened to liberate tantalum mineral particles. The slurry containing tantalum and waste material is concentrated to around 30 per cent tantalum oxide using predominantly gravity and magnetic separation techniques, again depending upon the characteristics of the ore.

⁵⁶ Gangue: waste material associated with ore minerals.

⁵⁷ Screw classifiers: a wet gravity separation method in which dense particles are removed from a slurry by a series of rotating rakes (similar to an Archimedes Screw)

⁵⁸ Gravity separation: the selective sorting of ore minerals by exploiting natural variations in mineral density.

⁵⁹ Froth flotation: the selective separation of hydrophobic (water-repelling) ore minerals from hydrophilic (water-attracting) ore minerals.

⁶⁰ Acid leaching: the process of extracting metal from a concentrate using mineral acids.

⁶¹ Desliming: the removal of particles in the micron size range prior to processing.

⁶² Diamine collectors: a positively charged cationic collector used to float rare-metal oxides.

At the Greenbushes mine in Australia tin-tantalum ores are processed using a circuit of shaking tables, spirals and jigs⁶³. The rough concentrate is de-watered and dried producing a tantalum concentrate containing about four to six per cent tantalum oxide. High intensity magnetic separation is used to separate the paramagnetic⁶⁴ tantalum grains from the non-magnetic tin-tantalum grains; the paramagnetic fraction is further concentrated to around 30 per cent tantalum oxide by roasting. The non-magnetic fraction is further processed using a combination of froth flotation and roasting to remove sulphides, and smelting to separate tantalum from tin (Figure 4) (Fetherston, 2004).

Conversion to metal

Tantalum and niobium metal can be produced from three different compounds — fluorides, oxides and chlorides (Albrecht, 1989). The tantalum and niobium compounds are reduced to form pure metals and metal powders by two main methods.

A mixed niobium-tantalum concentrate is digested using a mixture of hydrofluoric and sulphuric acids. The niobium-tantalum-bearing acid solution is then treated using liquid-liquid separation methods, involving solvent extraction or ion exchange, to separate niobium from tantalum. Niobium and tantalum can be extracted from the hydrofluoric-sulphuric acid mixture by using organic solvents, such as cyclohexanone, tributyl phosphate (TBP) or methyl isobutyl ketone (MIBK), whilst leaving behind impurities such as iron, manganese, tin and titanium (Figure 5). Ion exchange is used to produce high-purity solutions of niobium and tantalum and is usually performed using an amine extractant in kerosene.

Niobium and tantalum are precipitated as hydroxides from the mixed organic solvent solution by the addition of ammonia (NH₃). The resultant hydroxides are calcined⁶⁵ in a furnace to form niobium and tantalum oxides. The process of sintering⁶⁶ the oxide products, with carbon, at high temperature is used to produce niobium and tantalum carbides. Niobium oxide is also the starting point for niobium metal production. The addition of potassium fluoride to the mixed organic solvent solution results in the crystallisation of potassium tantalum fluoride (K₂TaF₇), the pre-requisite for tantalum metal production (Figure 5).

⁶³ Shaking tables, spirals and jigs: water and gravity based separation devices.

⁶⁴ Paramagnetic: a form of magnetism that only occurs in the presence of an externally applied magnetic field.

⁶⁵ Calcined: a thermal process applied to ores in order to bring about decomposition, phase transitions or the removal of volatile matter (e.g. carbon dioxide and water).

⁶⁶ Sintering: a process of forming a coherent bonded mass by heating metal powders without melting.

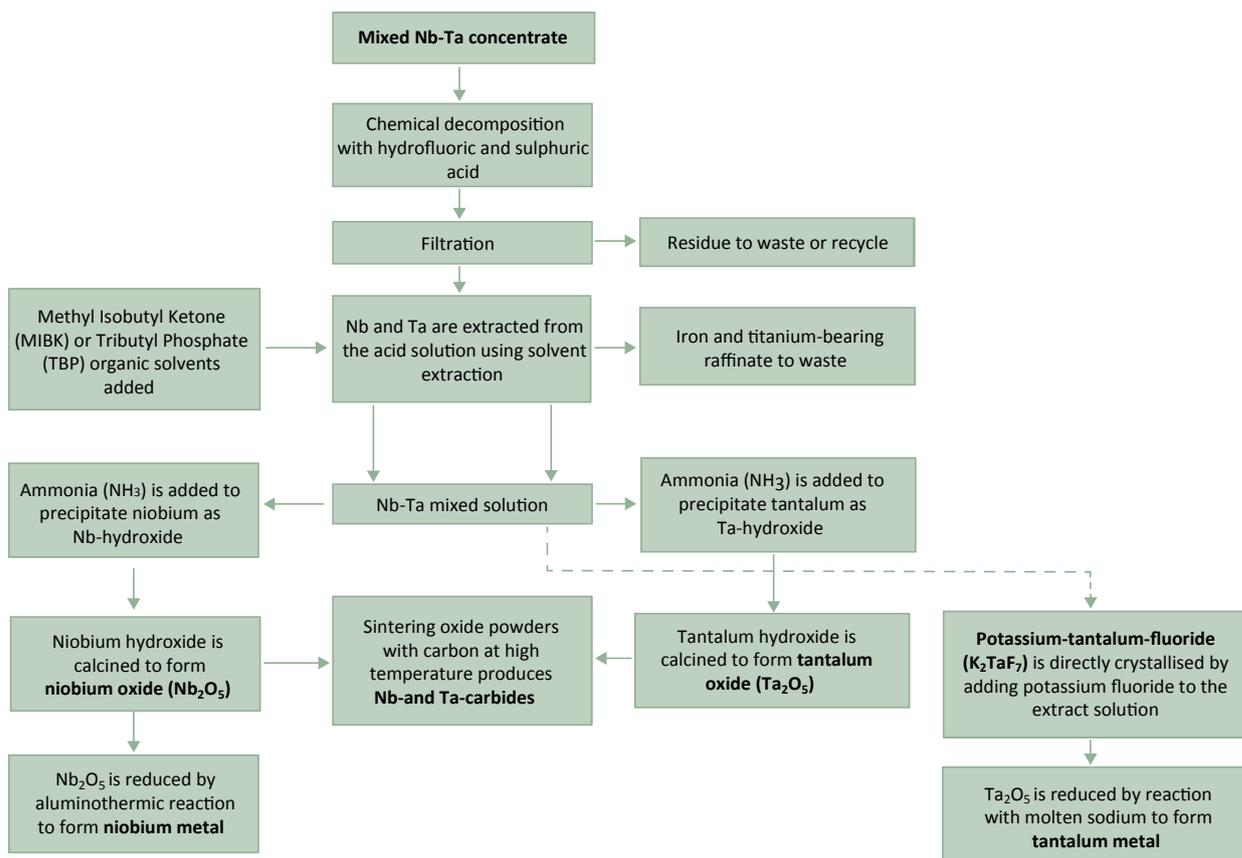


Figure 5 Chemical processing of niobium and tantalum concentrates.

Two slightly different production routes are available for the production of niobium metal: one is used to produce pure niobium metal and the other is used to produce ferro-niobium. High-purity niobium metal is produced by aluminothermic reduction⁶⁷ of high-purity niobium oxide with aluminium, lime and fluorspar. Electron beam melting is commonly used to increase the purity of niobium. To produce ferro-niobium, containing about 60 per cent niobium, iron oxide powder is added to the mixture prior to reduction (Albrecht, 1989).

The reduction of potassium tantalum fluoride by reaction with sodium is the most common method of producing tantalum metal. Potassium tantalum fluoride is blended with liquid sodium and inert salts to form a paste. The paste is then roasted in a continuous furnace to produce tantalum metal powder, potassium fluoride and sodium fluoride. To ensure a high degree of purity, as required by the electronics industry, the conversion process is performed using tantalum vessels under low-oxygen conditions. Further purification is achieved by vacuum arc furnace or electron beam melting⁶⁸ of tantalum powder (Albrecht, 1989).

⁶⁷ Aluminothermic reduction: an exothermic reaction involving aluminium oxide and iron oxide as reducing agents.

⁶⁸ Electron beam melting: a high-temperature (700-1000°C) vacuum furnace, utilising high-energy electron beams as a heat source.

Artisanal mining of coltan



Figure 6 Coltan (columbite-tantalite). Source: Sasha Lezhnev (© Enough Project)⁶⁹.

Although niobium and tantalum are extracted and processed conventionally, significant amounts are also extracted by artisanal and small scale mining (ASM).

Artisanal and small scale mining (ASM) is believed to provide a livelihood for over 100 million people worldwide

⁶⁹ Image taken by Sasha Lezhnev. © Enough Project. Used with Permission.

and is defined as mining activities that are labour-intensive but capital-, mechanisation- and technology-poor. ASM is characterised by:

- Poor occupational safety
- Poorly qualified and trained personnel
- Inefficiency in extraction and processing
- Low salaries
- Insufficient consideration of environmental issues

Additionally, ASM is often unregulated with many activities falling outside the host countries' legal framework (Hentschel *et al.*, 2003).

Certain minerals, such as gold, tin, tungsten and columbite-tantalite (coltan) (Figure 6), which are produced in significant quantities by ASM, can sometimes be mined in conditions of armed conflict and human rights violations. The mining of these minerals under such conditions has given rise to the term 'conflict minerals'. Their illicit mining is often organised by armed groups who use the profits from the sale of the conflict minerals to further their own ends and to finance further fighting.

Coltan is found in significant quantities in parts of central Africa, in particular the Democratic Republic of Congo (DRC). It is estimated that in 2009 over 50 per cent of global tantalum production was from Africa. In the DRC small scale mining of coltan, from either alluvial or pegmatite sources, is labour intensive and unregulated. Consequently it is difficult to accurately calculate the quantity of coltan mined and exported. It is believed that the majority of coltan mined in the DRC ends up in neighbouring countries such as Rwanda, Burundi and Uganda. It is estimated that rebel groups in the DRC made in excess of \$1 billion in 2009 through conflict mineral trading (Bunting, 2010).

Illegally traded coltan ore may end up in consumer electronic products throughout the world. Ore from Rwanda, Burundi or Uganda may be shipped to Asia for processing and smelting. Once processed it is impossible to determine the source of the original ore. The processed material may then be shipped to the western world for use in electrical components such as capacitors. Finally these components may be exported to Asia for inclusion in consumer electronic goods such as mobile phones (Figure 7).

Many non-governmental organisations (NGOs) and charities have initiated schemes aimed at alleviating the problems of ASM and conflict mineral trading. In addition some large electronics companies are now

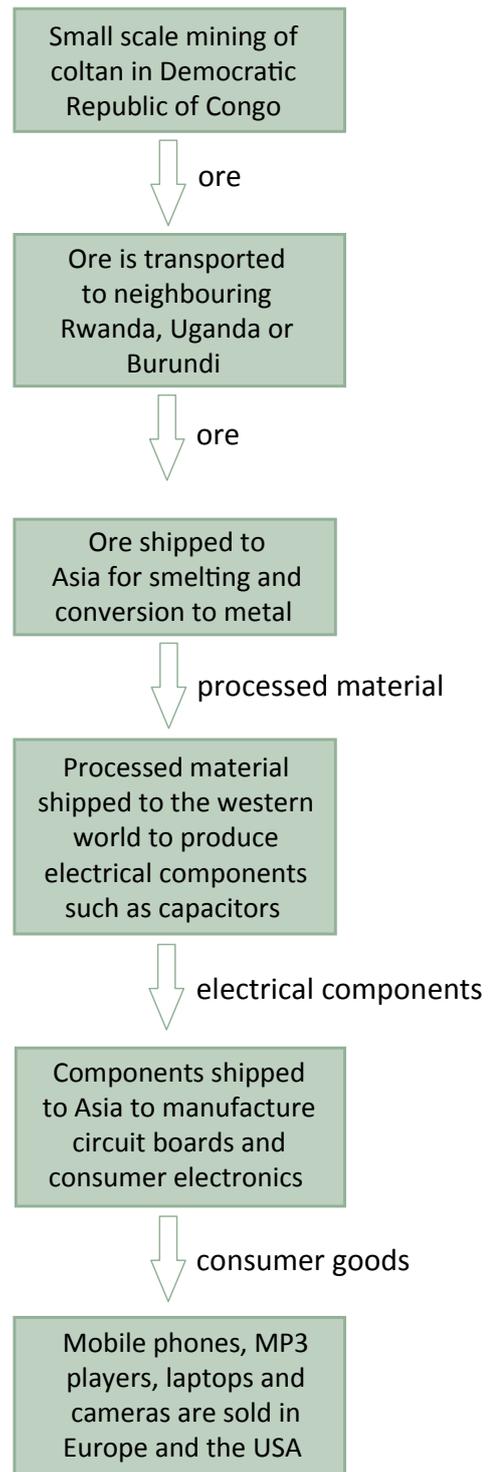


Figure 7 An example of a conflict mineral supply chain. Source: (Enough Project, 2011).

refusing to use conflict mineral-bearing components in their products. However, it is likely to prove difficult to completely avoid the use of these components for the reasons explained above. The success of these schemes also relies on the ability of countries like the DRC to monitor exports, control its army and combat rebel forces (Bunting, 2010).

Specifications and Uses

Specifications

Niobium and tantalum are utilised and traded in a variety of forms, the most significant of which are:

Niobium pentoxide (Nb_2O_5) is a colourless, unreactive solid produced in different grades at better than 99 per cent purity. It is generally the starting point for the production of other niobium compounds, such as niobium chloride ($NbCl_5$), niobium carbide (NbC) and lithium niobate ($LiNbO_3$).

Niobium carbide (NbC) is a very hard (Mohs hardness 8.5-9) refractory ceramic compound, formed by sintering a mixture of finely-ground niobium powder with an excess of carbon and heating to around 1800°C. Niobium carbide is a heavy, brown-grey metallic powder containing around 87 per cent niobium.

Niobium metal and metal powder is most commonly formed by the aluminothermic reduction of niobium pentoxide with further purification achieved by electron beam melting.

Ferro-niobium (60% Nb) contains about 60-70 per cent niobium and is produced by reducing a mixture of niobium pentoxide, iron oxide and aluminium oxide by aluminothermic reaction. Further purification is achieved by electron beam or vacuum arc furnace melting.

Potassium tantalum fluoride (K_2TaF_7) is the precursor to tantalum metal powder and is produced by reacting potassium fluoride with the tantalum-bearing extractant from solvent extraction.

Tantalum pentoxide (Ta_2O_5) is the starting point for other tantalum compounds including tantalum chloride ($TaCl_5$), tantalum carbide (TaC) and lithium tantalate ($LiTaO_3$).

Tantalum carbide (TaC) is an extremely hard (Mohs hardness 9-10) refractory ceramic compound, formed by sintering fine-grained tantalum powder with excess carbon in a furnace. The resulting tantalum carbide is a heavy, brown metallic powder containing in excess of 90 per cent tantalum by weight.

Tantalum metal and metal powder is formed by the reduction of potassium tantalum fluoride salts by sodium at around 800°C. Other methods of producing tantalum metal include carbothermic reduction⁷⁰ of tantalum

pentoxide and electrolysis⁷¹ of potassium tantalum fluoride salts. By double or triple melting, using arc-furnace or electron beam methods, a very high degree of purity can be achieved in the final product.

Lithium-niobate ($LiNbO_3$) and *lithium-tantalate ($LiTaO_3$)* are colourless, crystalline solids with unique optical and piezoelectric properties⁷².

Uses

The unique properties of niobium and tantalum make them vital components in a diverse range of products and applications (Table 4 and 5). These properties include:

- superconductivity⁷³
- corrosion-resistance
- very high melting temperatures
- shape memory properties⁷⁴
- high coefficient of capacitance⁷⁵
- bio-compatibility⁷⁶

About 89 per cent of global niobium production is used to produce ferro-niobium, used in high strength low alloy steels; the remaining 11 per cent is used in the manufacture of niobium alloys, niobium chemicals and carbides, high-purity ferro-niobium, and other niobium metal products. Between 2004 and 2010 the production of both niobium chemicals and niobium alloys has increased whilst production of niobium metal products and high-purity ferro-niobium has decreased (Figure 8).

In 2010 almost 18 per cent of tantalum production is used to manufacture tantalum chemicals. A further 17 per cent is used in the manufacture of metallurgical grade powders while capacitor-grade powder production is the largest end-use of tantalum at about 24 per cent. Although some sources suggest that capacitor-grade powder may account for about 48 per cent. Tantalum metal products, ingot and carbides make up the remaining 41 per cent of end-uses. Metallurgical grade powders, chemicals, tantalum ingots and metal products all represent growth areas during the period between 2004 and 2010. The production of both carbides and capacitor-grade powders has decreased during the same period of time (Figure 9).

⁷¹ Electrolysis: a method of reducing metals from metallic compounds to obtain the pure metal.

⁷² Piezoelectric: the accumulation of electrical charge in a material in response to mechanical strain.

⁷³ Superconductivity: a zero electrical resistance occurs in some materials at low temperature.

⁷⁴ Shape memory properties: the ability of an alloy to 'remember' its original cold-formed shape; returning to the pre-deformed shape upon heating.

⁷⁵ Co-efficient of capacitance: the ability of a solid to store an electrical charge.

⁷⁶ Bio-compatibility: the ability of a prosthesis implanted in the body to exist in harmony with tissue without causing damaging changes.

⁷⁰ Carbothermic reduction: an exothermic reaction involving carbon as a reducing agent.

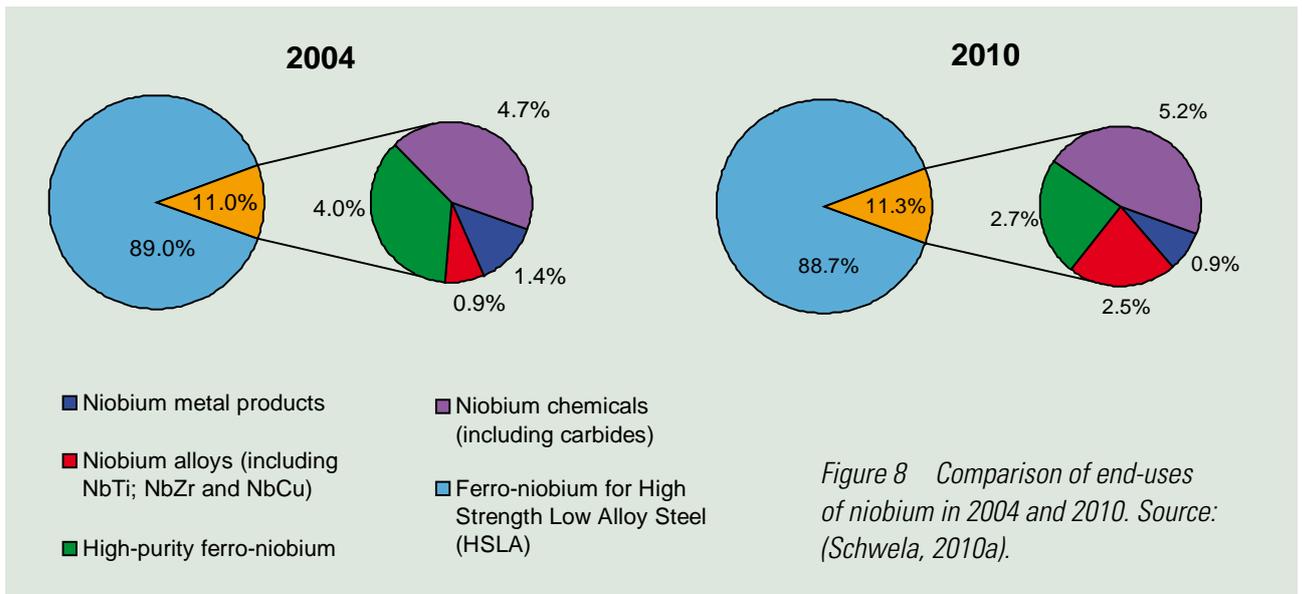


Figure 8 Comparison of end-uses of niobium in 2004 and 2010. Source: (Schwela, 2010a).

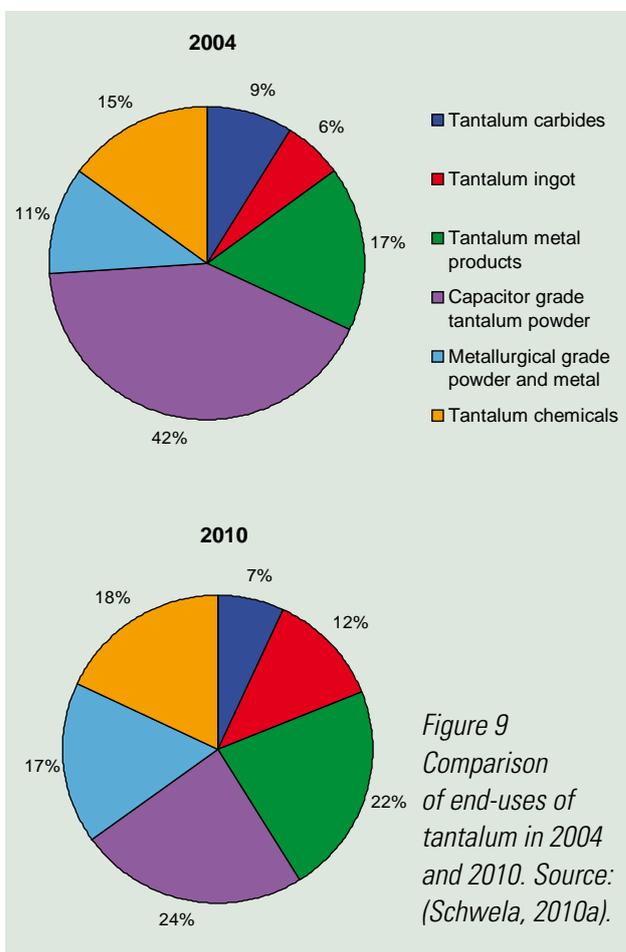


Figure 9 Comparison of end-uses of tantalum in 2004 and 2010. Source: (Schwela, 2010a).

Steel and other alloys

Niobium and tantalum are both used in the production of alloys. Niobium, in the form of ferro-niobium, is used in the production of high strength low alloy steels (HSLA). The addition of niobium to steel increases strength, reduces grain boundary deformation⁷⁷ and reduces weight. HSLA steels are

⁷⁷ Grain boundary deformation: the process by which grains may move past each other in response to a change in grain shape.

used to manufacture vehicle bodies, ship hulls, railway tracks, and oil and gas pipelines. They also provide cathode protection⁷⁸ to large steel structures such as oil platforms. Tantalum is also used in applications where corrosion resistance is required such as chemical processing equipment (Figure 10) and rust-free fastenings. The bio-compatibility of tantalum-alloys with human tissue is utilised in the production of prosthetic joints and medical devices such as pace makers.

Other metals which are used in alloys with niobium include zirconium, titanium and tin. These alloys are extremely corrosion resistant and are used to manufacture chemical processing equipment and pipelines. Niobium-titanium and niobium-tin alloys can also be used to produce superconducting magnets required for medical imaging equipment, such as magnetic resonance imaging (MRI) scanners. Tantalum-ruthenium alloys are used in a number of military applications because of the shape memory properties. Such alloys can be bent, compressed or deformed but are capable of regaining their shape on heating to 1120°C.

Vacuum grade ferro-niobium⁷⁹ and tantalum are important constituents of superalloys⁸⁰ used in high-temperature, high-stress applications. Examples of niobium superalloys include Inconel 718[®], which contains about five per cent niobium and C103[®], used in rocket thruster nozzles, which contains about 89 per cent niobium. Tantalum superalloys, Rene N6[®] and CSMX-10[®], used in high-temperature, high-stress applications such as gas turbine blades, typically contain between two and 8.5 per cent tantalum. Many superalloys contain

⁷⁸ Cathode protection: a technique for reducing corrosion of a metal surface by making it the cathode of an electrochemical cell.

⁷⁹ Vacuum grade ferro-niobium: ferro-niobium produced using high-purity niobium oxide and vacuum arc furnace melting.

⁸⁰ Superalloys: are high-performance alloys that have exceptional mechanical strength and creep resistance at temperatures above 700°C, and resistance to oxidation and corrosion.



Figure 10 Tantalum and niobium are used in the manufacture of chemical processing equipment.

Source: © Corbis.

appreciable amounts, up to 50 per cent, of nickel, cobalt, or nickel-iron; other elements also used in alloy mixtures include chromium, aluminium, molybdenum, titanium and hafnium.

Carbides

Niobium and tantalum carbides are extremely hard, refractory ceramic substances that are often used in high-stress, high-temperature applications. Tantalum and niobium carbides, in the form of TaNbC⁸¹, WTiTaC⁸² or WTiTaNbC⁸³, may be added

⁸¹ TaNbC: tantalum-niobium-carbide.

⁸² WTiTaC: tungsten-titanium-tantalum-carbide.

⁸³ WTiTaNbC: tungsten-titanium-tantalum-niobium-carbide.

to tungsten carbide in the manufacture of industrial high-speed cutting and boring tools, teeth for excavator buckets and drill bits for the mining industry. Carbides are also used as refractory coatings in nuclear reactors and furnaces.

Cemented carbide, also known as hard metal, is a composite of various metal carbides cemented into a compact mass using a cobalt or nickel binder. On account of their very high strength and resistance to corrosion and abrasion, hard metals are also used in high-speed drilling and cutting tools. Such a hard metal composite may contain 73.5 per cent tungsten carbide, 10.5 per cent tantalum carbide, seven per cent titanium carbide, and nine per cent cobalt binder.

Thin coatings of niobium or tantalum carbide may be applied to surfaces using either chemical vapour deposition (CVD), or physical vapour deposition (PVD)⁸⁴ techniques. Carbide coatings often increase strength and improve wear resistance, increasing the life of tool cutting edges.

Powders

Niobium and tantalum powders are used in a wide range of applications and are often the precursor to a number of products containing these metals, for example, alloys, abrasion- and corrosion- resistant coatings, and structural

⁸⁴ Vapour deposition: a process of thin film deposition used to manufacture high-purity, high-performance solid materials.

Industry	Usage	Niobium product
Automotive	Vehicle bodies	HSLA ferro-niobium (60% Nb)
Ceramics and surface coatings	Ceramic capacitors, glass coatings and camera lenses	Niobium oxide
Chemicals	Chemical processing equipment and oil and gas pipelines	HSLA ferro-niobium (60% Nb), niobium metal and niobium-1% zirconium alloy
Construction	Architectural steels and cathode protection systems for large steel structures	HSLA ferro-niobium (60% Nb), niobium metal
Engineering	Cutting tools, railway tracks and ship hulls	Niobium carbide
Electronics	Capacitors, street lighting systems and surface acoustic wave filters for sensor and touchscreen technologies	Niobium powder, niobium oxide and lithium niobate
Medicine	Superconducting magnetic coils in MRI scanners and magnetoencephalography (brain activity mapping)	Niobium-titanium alloy, niobium-tin alloy and niobium nitride
Metallurgical	Superalloys for jet engines and turbine blades	Vacuum-grade ferro-niobium and vacuum-grade nickel-niobium
Physics	Particle physics research	Niobium-titanium alloy and niobium-tin alloy

Table 4 Summary of the main uses of niobium by industry sector. Source: (TANB, 2011a).

ceramics. High-purity tantalum powder is primarily used in the production of capacitors because of its ability to hold an electrical charge. Even though the quantity used in each capacitor is very small this is a very significant application because an average mobile phone contains 23 tantalum capacitors (MBM, 2006) and global production of new mobile phones in 2010 was 417 million. Tantalum powders for capacitor production are made in three forms: angular powders for high-voltage applications; nodular powders for low-voltage, high-capacitance applications; and flake powders for medium-voltage, medium-capacitance uses. Niobium powder is also used to manufacture capacitors but they are commonly larger and have a shorter life span than tantalum-based capacitors.

Chemicals

Niobium and tantalum oxides are commonly used in the production of speciality glass and structural ceramics. Examples include high refractive index glass for camera and eyeglass lenses, niobium- and tantalum-doped ceramics for use in capacitors and high-performance bearings.

Lithium niobate and lithium tantalate are chemical compounds with unique optical, piezoelectric and pyroelectric⁸⁵

⁸⁵ Pyroelectric: the ability of a material to generate a temporary voltage when heated or cooled.

properties. They are primarily used in the manufacture of electronic components, such as capacitors and surface acoustic wave filters, which are employed in devices such as mobile phones, motion detectors and laser switching devices, used in range finding applications. They are also used in touchscreen technologies.

Niobium nitride is an important component of superconducting magnets, used in MRI scanners. Tantalum nitride is an effective semi-conductor used in numerous electronic applications such as light emitting diodes (LED), solar cells, transistors and digital circuits.

World resources, reserves and production

Resources⁸⁶ and reserves⁸⁷

Unlike many other metals global resource and reserve data for niobium and tantalum are not well documented. However, primary reserves and resources of niobium and tantalum are

⁸⁶ Mineral resources: a mineral resource is a concentration of minerals or a body of rock that is, or may become, of potential economic interest for the extraction of a mineral commodity.

⁸⁷ Mineral reserves: a mineral reserve is the part of the resource which has been fully geologically evaluated and is commercially and legally minable using current technology.

Industry	Usage	Tantalum product
Automotive	Anti-lock brake systems, airbag activation systems and engine management modules	Tantalum powder
Ceramics and surface coatings	Ceramic capacitors, glass coatings, camera lenses and X-ray film	Tantalum oxide and yttrium tantalate
Chemicals	Chemical processing equipment	Tantalum metal
Construction	Cathode protection systems for large steel structures such as oil platforms and corrosion resistant fasteners such as screws, and nuts and bolts	Tantalum metal (sheets, rods, plates and wire)
Engineering	Cutting tools	Tantalum carbide
Electronics	Capacitors, surface acoustic wave filters for sensor and touchscreen technologies, hard disc drives, and LED lights	Lithium tantalate, tantalum powder, tantalum ingots and tantalum nitride
Medicine	Pace makers, hearing aids and prosthetic devices such as hip joints	Tantalum metal
Metallurgical	Furnace parts, superalloys for jet engines and rocket engine nozzles	Tantalum metal and tantalum ingots
Military	Missile parts, ignition systems, night vision goggles and Global Positioning Systems (GPS)	Tantalum ingots and tantalum oxide

Table 5 Summary of the main uses of tantalum by industry sector. Source: (TANB, 2011b).

Source	Proved and probable reserves (tonnes)	Contained Nb ₂ O ₅ (tonnes)	Inferred resources (tonnes)	Contained Nb ₂ O ₅ (tonnes)
Brazil	452 200 000	11 142 740	11 900 000	214 200**
Canada	32 086 000	179 682	37 912 000	219 889
United States	150 000*	----	----	----
Total	484 436 000	11 322 422	n.a.	n.a.

* Deemed uneconomic at 2010 prices (Papp, 2011a)

** Only includes resources from Catalão (AngloAmerican, 2011)

Table 6 Estimated global reserves and resources of niobium ore. (Iamgold, 2009, AngloAmerican, 2011, CBMM, 2011, Papp, 2011a). Total resources are not reported as not all countries are included.

estimated to be more than sufficient to meet global demand for the foreseeable future, at least the next 500 years.

Niobium resources and reserves

Niobium resources are almost exclusively located in Brazil and Canada. However, other countries with unquantified niobium resources include Egypt, Malawi and Greenland. Global niobium ore reserves, proved and probable, are estimated to be in the region of 485 million tonnes with over 93 per cent occurring in Brazil and the remaining seven per cent occur in Canada (Table 6).

Tantalum resources and reserves

Tantalum ore resources and reserves are located in a greater number of countries than those of niobium and are estimated to be about 317 000 tonnes and almost 153 000 tonnes respectively, according to the Tantalum-Niobium International

Study Centre and the National Department of Mineral Production (DNPM–Brazil). Brazil has the largest share of resources at approximately 40 per cent. The remaining 60 per cent occur in Australia, Asia, Russia and the Middle East, Africa, North America and Europe (Table 7).

Production

Niobium production

World production of niobium rapidly increased from approximately 20 000 tonnes in 1997 to over 100 000 tonnes in 2009 (Figure 11). The primary source of niobium is the mineral pyrochlore, accounting for approximately 98 per cent of the total, with only minor production coming from the production of columbite and tin-slugs. The increase in niobium production is linked to growing consumption of HSLA, used in the manufacture of cars, buildings, ships and refinery equipment. Demand for these steels is linked

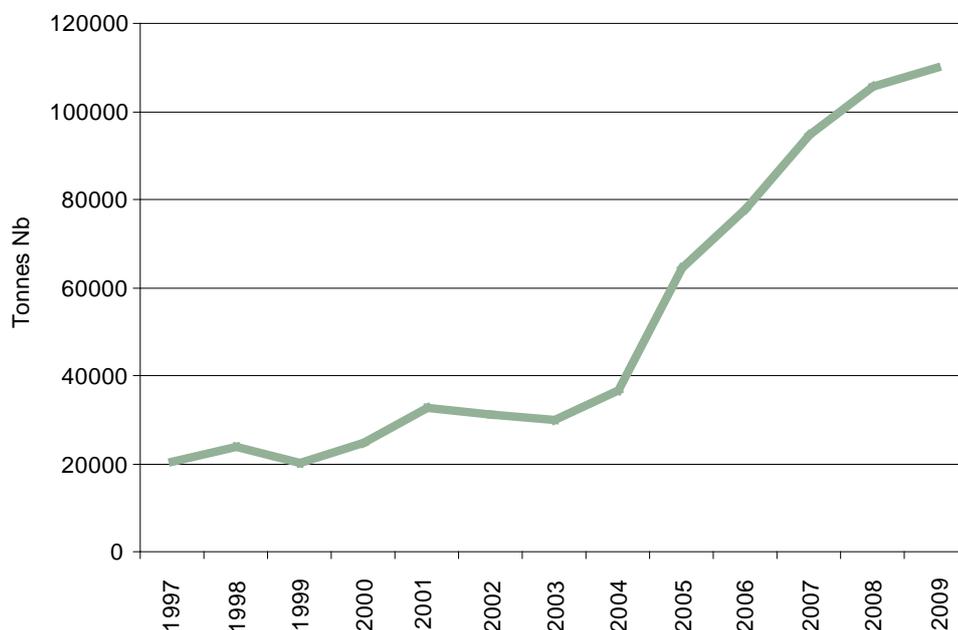


Figure 11 Global niobium production (based on the niobium content of mined ore) between 1997 and 2009. Source: World Mineral Statistics database, British Geological Survey.

Source	Most likely resource base ⁸⁸ (tonnes Ta ₂ O ₅)	Percentage of resources	Reserves (tonnes Ta)
Brazil	129 274	40	87 360
Australia	65 771	21	40 560
China and Southeast Asia	33 112	10	7 800
Russia and Middle East	31 298	10	----
Central Africa	28 576	9	3 120
Other Africa	21 318	7	12 480
North America	5443	2	1 500*
Europe	2268	1	----
Total	317 060	100	152 820

*Deemed uneconomic at 2010 prices (Papp, 2011b)

Table 7 Estimated global tantalum reserves and resources. (Papp, 2011b, Schwela, 2010a, DNPM, 2009).

particularly to the recent industrial development of nations such as China and India, and the rapid growth of the global population. For example, in 1997 annual car production was around 53 million vehicles compared with nearly 62 million in 2009 (OICA, 2011).

The increased demand for niobium may also be attributed to its use in mobile telephones, superconducting magnets,

(such as used in the Large Hadron Collider), glass and camera lens coatings, superalloys and functional and structural ceramics.

In 1997 Brazil accounted for approximately 88 per cent of world niobium production. This figure has since risen to about 95 per cent. Canada is responsible for the majority of remaining production (Figure 12).

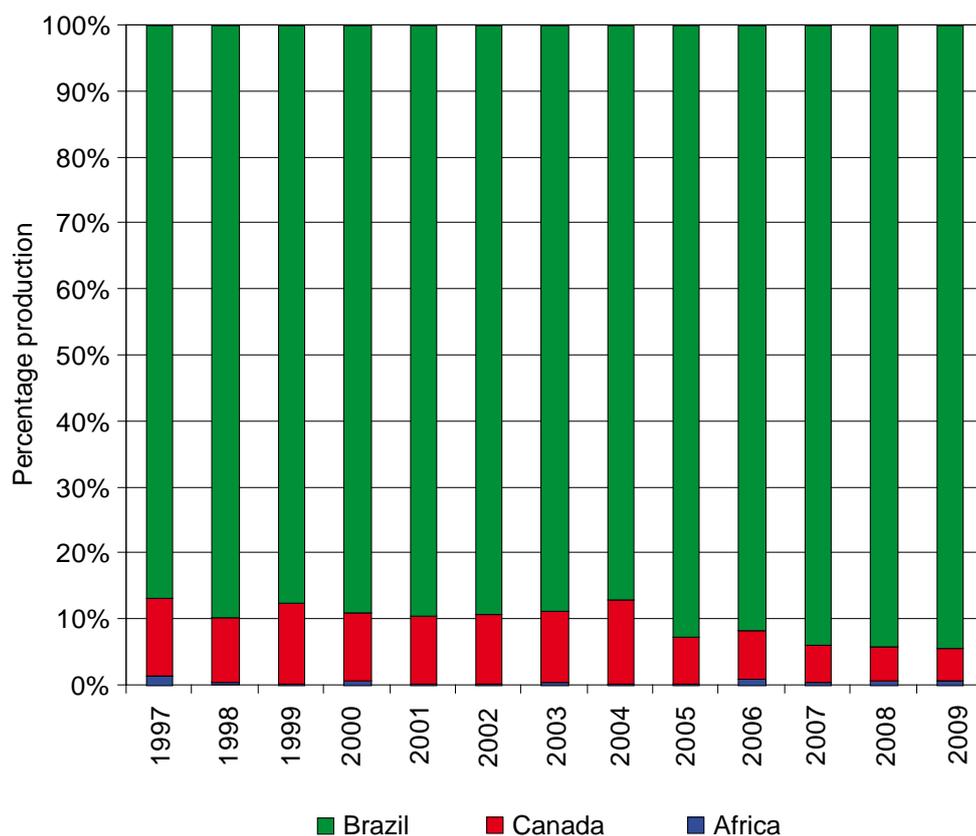
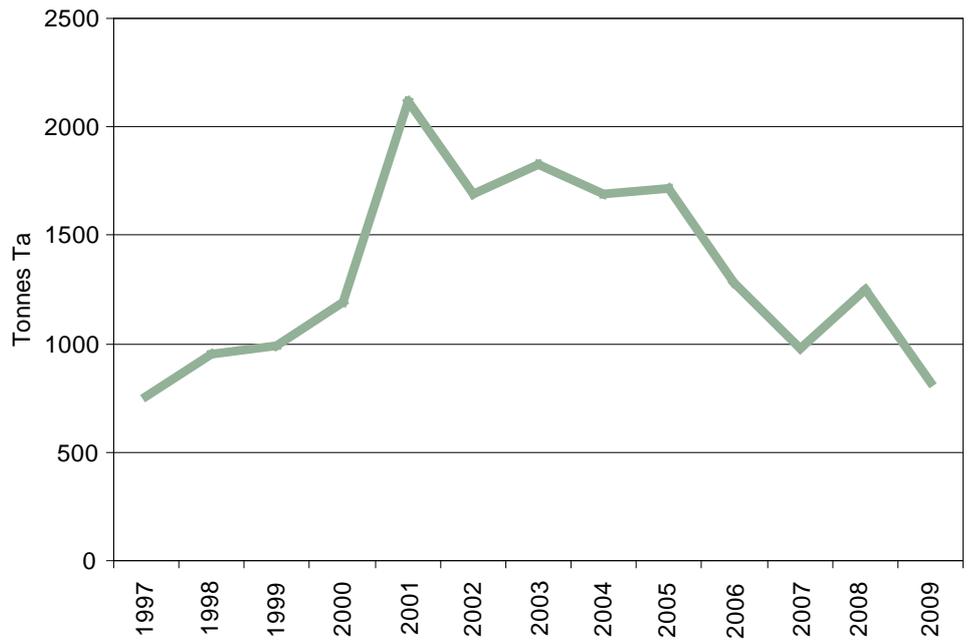


Figure 12 Global niobium production by country between 1997 and 2009. Source: World Mineral Statistics database, British Geological Survey.

Figure 13 Global tantalum production (based on the tantalum content of mined ore) between 1997 and 2009. Source: World Mineral Statistics database, British Geological Survey.



Tantalum production

Global tantalum production peaked in 2001 at just over 2000 tonnes; since then it has declined to about 900 tonnes in 2009 (Figure 13). About half of all tantalum production is associated with the primary ore mineral tantalite, while the remainder comes from tin-slag material and other concentrates such as struverite and columbite-tantalite. Demand for tantalum is driven mainly by the electronics industry where it is a vital component in a wide range of consumer products.

The recent decline in tantalum production is related to the temporary closure of both the Wodgina and Greenbushes mines, in Australia. These operations were placed on care and maintenance due to the drop in the price of tantalum, as a result of the economic downturn, and the increased volume of conflict tantalum entering the market from the DRC.

Unlike niobium, production of tantalum is much more widespread although Africa, predominantly Rwanda

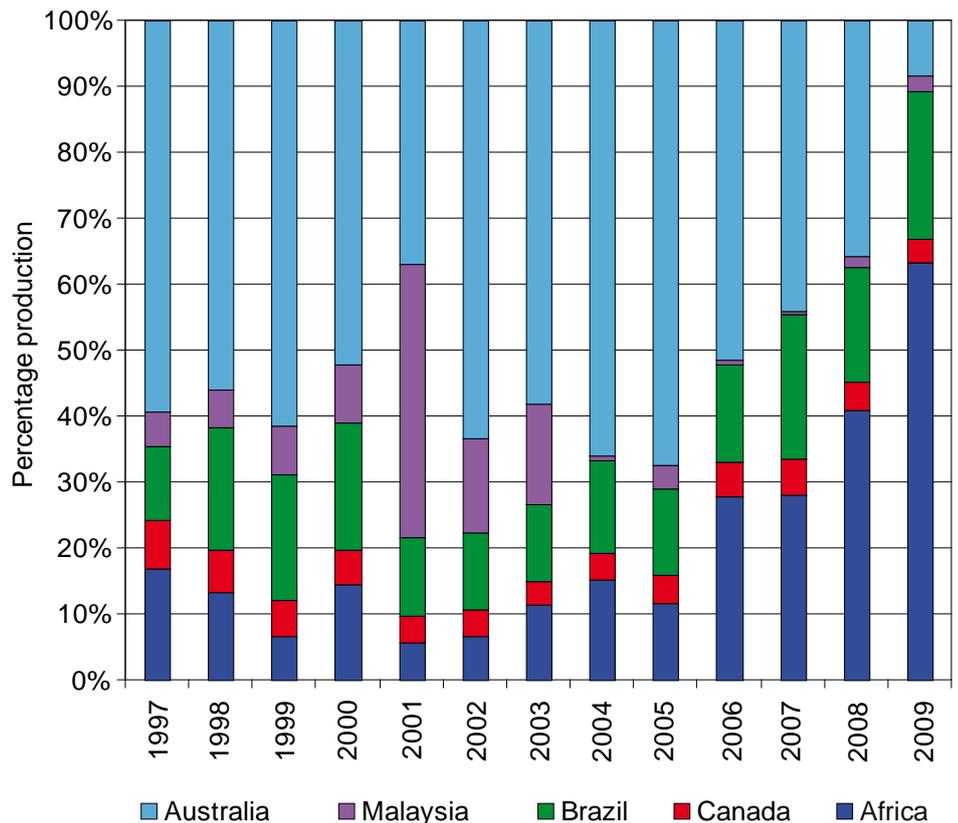


Figure 14 Global tantalum production by country between 1997 and 2009. Source: World Mineral Statistics database, British Geological Survey.

and Democratic Republic of Congo, accounted for over 60 per cent of global tantalum production in 2009. In 2002 Australia produced about 60 per cent of global tantalum but this figure dropped to less than ten per cent in 2009 due to the temporary closure of the Wodgina and Greenbushes mines. Additional production comes mostly from Brazil (about 20 per cent in 2009) with minor amounts also produced in Malaysia and Canada (Figure 14).

Projects under development

The growing markets for niobium and tantalum have led to an increase in exploration for niobium and tantalum in recent years. Many of the deposits being investigated contain both metals but, in many cases one is predominant. Current exploration for both metals is focussed on carbonatite, peralkaline granite-hosted and LCT-type granite-hosted deposits (Table 8).

Global Advanced Metals (GAM), formerly Talison Metals, has re-started mining at its Wodgina operation in Australia. Tantalum pentoxide will be produced at Wodgina at a rate of 318 tonnes per year, although at full capacity it could be double that quantity. Material from Wodgina will be processed at Global Advanced Metals' Greenbushes operation. Mining is not currently taking place at Greenbushes (Schwela, 2010b).

Australia-based Gippsland Ltd is developing a huge tantalum-tin resource in Egypt. The project includes the 44.5 million tonne Abu Dabbab deposit, scheduled for production by 2013, and the 98 million tonne Nuweibi project. The company plans to produce about 300 tonnes of tantalum pentoxide a year from its Abu Dabbab operation (Gippsland, 2011).

Globe Metals and Mining also plans to bring its Kanyika project in Malawi into full production by 2013. The operation will produce approximately 200 tonnes of ferro-niobium, and 190 tonnes of tantalum pentoxide per year. The operation will also produce by-product uranium oxide and zirconium silicate (Schwela, 2010b).

Australian company, Ram Resources Ltd, has acquired 51 per cent of the Motzfeldt polymetallic deposit in southern Greenland. Motzfeldt has the potential to be a giant niobium-tantalum deposit with possible by-product rare earth elements. The overall resource could be in the region of 500 million tonnes although further work is required to define a JORC compliant estimate (RamResources, 2011).

World trade

It is difficult to obtain trade data specific to niobium and tantalum as they are commonly reported under a combined

Deposit	Location	Company	Type	Resources* (Mt)	% Nb ₂ O ₅	% Ta ₂ O ₅
Anita	Canada	Les Mineraux Crevier	Carbonatite-nepheline syenite	23.75	0.186	0.019
Motzfeldt	Greenland	Ram Resources	Alkaline-peralkaline granite	500	0.13–0.15	0.011–0.013
Crevier	Canada	MDN Inc.	Carbonatite-nepheline syenite	25.4	0.2	0.023
Kanyika	Malawi	Globe Metals and Mining	Alkaline-peralkaline granite	21	0.41	0.018
Abu Dabbab	Egypt	Gippsland	LCT granite	44.5	n.a.	0.025
Nuweibi	Egypt	Gippsland	LCT granite	98	0.0095	0.014
Marropino	Mozambique	Noventa	LCT granite	7.4	n.a.	0.023
Upper Fir	British Columbia	Commerce Resources Corp.	Carbonatite-nepheline syenite	36.4	0.17	0.019

*Includes all categories of resource

Table 8 Selected niobium-tantalum projects under development. (Schwela, 2010b, Gippsland, 2011, RamResources, 2011).

trade code with vanadium and rhenium. This uncertainty is compounded by the fact that niobium and tantalum are traded in a variety of forms including metallurgical products, ores and concentrates, and chemicals.

Due to concerns over future access to niobium and tantalum ores, and because for many applications effective substitutes are not available, the European Commission (EC) has identified niobium and tantalum as 'critical' raw materials (EC., 2010). This means that the EC considers there to be a potential risk of supply shortage with an associated impact on the EU economy. Strategies are being considered to mitigate against these supply risks. These include the promotion of sustainable development practices, improved resource efficiency and increased recycling.

The EU does not currently produce any niobium or tantalum and consequently it is entirely dependent on imports from other countries.

Brazil is the world's largest exporter of niobium, in the form of ferro-niobium, niobium oxide and niobium metal. Canada is the second largest exporter of niobium. Significant importers of these materials include Germany, the United States, Japan and China.

In 2009, Brazil supplied the United States with about 69 per cent of its ferro-niobium, 91 per cent of its niobium metal and 86 per cent of its niobium oxide. Mozambique (48 per cent) and Canada (32 per cent) were the main suppliers of niobium ores and concentrates to the United States (Figure 15). Comparable data for other major importing countries is not available.

South America (Brazil) and Central Africa have recently overtaken Australia as exporters of tantalum, although this

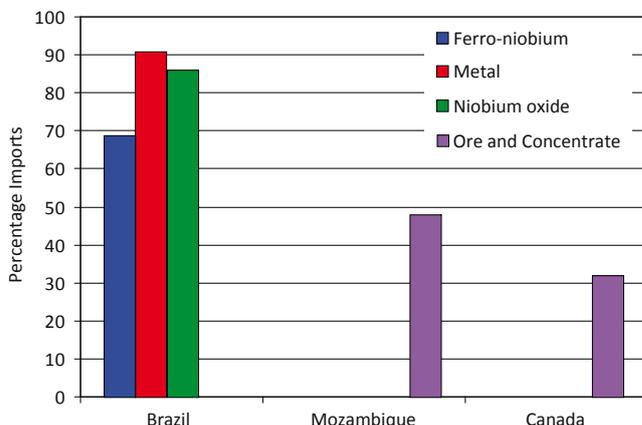


Figure 15 Sources of United States niobium imports in 2009 (Papp, 2011a).

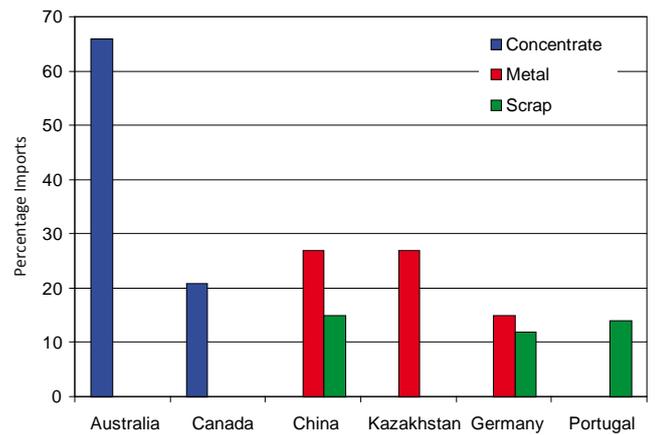


Figure 16 Sources of United States tantalum imports in 2009 (Papp, 2011b).

is likely to change with the re-opening of Wodgina and Greenbushes mines. A number of countries currently trade tantalum manufacturing and processing waste including Germany, Japan and China. The majority of tantalum exports are in the form of tantalum oxide or as the potassium salt. Currently the main exporters of tantalum ores, scrap, and tin slags to the EU include Japan, China and Kazakhstan.

In 2009, Australia supplied the United States with about 66 per cent of its tantalum concentrate whilst Canada supplied a further 21 per cent. The main exporters of tantalum metal to the United States were China (27 per cent), Kazakhstan (27 per cent) and Germany (15 per cent); tantalum scrap imports into the United States came from China (15 per cent), Germany (12 per cent) and Portugal (14 per cent) (Figure 16).

Prices

Unlike many other metals niobium and tantalum are not openly traded on any metal exchange; contract prices are negotiated between buyer and seller and generally remain confidential. Trade journals sometimes report indicative prices based on interviews with buyers and sellers.

Prior to 2007 ferro-niobium prices lay in the range US\$12 to 14 per kilogram. However, as of February 2011, prices were reported to be about US\$39 to 41 per kilogram, possibly due to increased demand (RamResources, 2011, Burns, 2009).

Tantalum is traded in three forms, each commanding a different price: in February 2011 tantalum ore and concentrate was about US\$120 per pound; tantalum oxides and salts about US\$240 per pound; and capacitor-grade tantalum powder in excess of US\$300 per pound (Reisman, 2011).

Recycling and substitution

Recycling

Both niobium and tantalum can be recovered from waste metals and scrap and in both cases account for up to 20 per cent of total supply (EC., 2010). Niobium is primarily recovered from niobium-steels and superalloys, but the amount recovered from other sources is minor. Tantalum is recovered from a number of different items including cemented carbides and alloys; however, recycling from capacitors is difficult and current technology is poorly developed. Other items from which tantalum can be recovered include spent sputtering targets⁸⁸, and edge trimmings and shavings from metallurgical processes.

Substitution

Many of the uses of niobium and tantalum are very specific and substitutes often incur a cost or performance penalty. Due to the physical and chemical similarities of niobium and tantalum the two metals can be substituted for each other in a number of applications, for example, in corrosion-resistant coatings. Where strength at high temperature is required in steel, metals such as molybdenum and vanadium are often used as substitutes for niobium and tantalum. Efforts are currently being made to substitute tantalum by aluminium or ceramics (Table 9 and 10). Some applications are unique and as such suitable substitutes are currently not available, for example, porous tantalum alloys used in the manufacture of prosthetic body parts.

Niobium product/application	Possible substitutes
HSLA steels	Molybdenum and vanadium
Stainless and high-strength steels	Tantalum and titanium
High-temperature applications	Ceramics, molybdenum, tantalum and tungsten

Table 9 Potential niobium substitutes. (Papp, 2011a).

Tantalum product/application	Possible substitutes
Capacitor manufacture	Aluminium and ceramics
Carbide material production	Niobium
Corrosion-resistant equipment	Glass, niobium, platinum, titanium and zirconium
High-temperature applications	Hafnium, iridium, molybdenum, niobium, and tungsten

Table 10 Potential tantalum substitutes. (Papp, 2011b).

⁸⁸ Sputtering target: metallic materials used as targets for the deposition of thin-films of tantalum compounds (e.g. tantalum carbide).

Focus on Britain

Niobium and tantalum have never been commercially exploited anywhere in Britain, and there has been no systematic evaluation of niobium and tantalum resources. Locations of potential interest are confined to alkaline and associated igneous rocks which are relatively rare in the UK.

Carbonatites and associated rocks

The only confirmed carbonatite body in the UK is associated with the Silurian⁸⁹ alkaline Loch Borrallan Complex in the north-west Highlands of Scotland. The whole of the Loch Borrallan Complex (including the carbonatite and associated ultramafic rocks) has generally low bulk-rock niobium contents, and niobium-bearing minerals such as pyrochlore are not present (Young *et al.*, 1994).

Carbonate veins and evidence of sodium metasomatism (finitisation) have been found at several localities along the Great Glen Fault near Inverness, and have been attributed to carbonatitic magmatism. Bulk-rock analyses indicate that niobium contents in the carbonate and fenite veins are higher than in the surrounding country rocks, but niobium-bearing minerals such as pyrochlore have not been found (Garson *et al.*, 1984). These veins are of relatively limited extent, but it is possible that a larger carbonatite mass may exist at depth.

Alkaline to peralkaline granites and syenites

Alkaline igneous rocks in the British Isles were formed during three main magmatic episodes: the Caledonian magmatism (Silurian to Devonian); the Permo-Carboniferous⁹⁰; and the Palaeogene⁹¹.

Caledonian igneous rocks are widespread, but the vast majority are calc-alkaline in composition. A suite of alkaline, largely syenitic, plutons occurs in the north-west Highlands of Scotland, but all these intrusions are characterised by low bulk-rock niobium contents (Fowler *et al.*, 2008). Niobium- and tantalum-bearing minerals have not been recognised in these syenites. In Wales, Ordovician to Silurian alkaline microgranites with relatively high bulk-rock niobium contents (up to 150 ppm) occur both in Snowdonia and the Llŷn Peninsula. The Mynydd Mawr microgranite in Snowdonia has been reported to contain niobium and tantalum minerals (Bevins and Mason, 2010, Young *et al.*, 2002).

⁸⁹ Silurian: a unit of geological time between 443 and 416 million years ago.

⁹⁰ Permo-carboniferous: a unit of geological time around 300 million years ago that represents the end of the Carboniferous and the start of the Permian.

⁹¹ Palaeogene: a unit of geological time between 65 and 23 million years ago.

Alkaline magmatism was extensive in central to southern Scotland and northern England during the Carboniferous⁹² and Permian periods, but the majority of the exposed igneous rocks are mafic volcanic rocks. More highly evolved magmatic rocks form a set of small plugs⁹³ and laccoliths⁹⁴ concentrated in central Scotland, which are typically trachytic⁹⁵ in composition. These trachytic igneous masses have relatively high bulk-rock niobium contents, up to 180 ppm (Upton *et al.*, 2007), but there are no records of niobium-bearing minerals being concentrated through either magmatic or hydrothermal processes.

The British Palaeogene igneous province extends along the western side of Britain, from the Bristol Channel to St Kilda and into Northern Ireland. The majority of these rocks are tholeiitic⁹⁶ to alkali basaltic in composition, but some more evolved rocks are present, chiefly as granitic plutons. Trace element data for these granites generally indicate low to moderate bulk-rock niobium contents (< 50 ppm). Fergusonite, a niobium- and tantalum-bearing oxide, has been reported from the northern Arran granite, where it occurs in miarolitic⁹⁷ cavities (Hyslop *et al.*, 1999). Columbite has been reported from the Lundy Granite (Thorpe *et al.*, 1995).

Granites and pegmatites of the LCT family

A number of large Palaeoproterozoic granitic pegmatites occur on the island of South Harris, in the Outer Hebrides. These have typical LCT mineral assemblages, including muscovite, biotite, beryl and rare tourmaline. The Chaipaval pegmatite, which has previously been quarried for alkali feldspar, also contains columbite and pyrochlore (von-Knorring and Dearnley, 1960). Pegmatites of this age occur across much of the Archaean Lewisian Gneiss Complex of north-western Scotland, but niobium and tantalum minerals have not been recorded elsewhere in this area.

LCT-type mineralisation is rare in granitoids of Caledonian age. At Carrock Fell in the Lake District, tungsten-bearing mineral veins occur within the Skiddaw Granite; columbite has also been described from these veins (Young, 1987). In the Cairngorm Granite in Scotland, fergusonite, columbite, ilmenorutile and cassiterite have been found in stream-sediment samples, but the source of these minerals has not been investigated in detail (IGS, 1975).

⁹² Carboniferous: a unit of geological time between 359 and 299 million years ago.

⁹³ Plug: a small, cylindrical, body of igneous rock, emplaced beneath the Earth's surface.

⁹⁴ Laccolith: a body of igneous rock, emplaced beneath the Earth's surface, which is circular in plan, with a flat floor and a shallow domed roof.

⁹⁵ Trachytic: a fine-grained type of igneous rock containing abundant amounts of a mineral called alkali feldspar; the fine-grained equivalent of syenite.

⁹⁶ Tholeiitic: a certain suite of igneous rocks with distinct chemistry typically formed in the oceans or at continental margins.

⁹⁷ Miarolitic: a term for crystal-lined cavities commonly found in granites and granitic pegmatites.

The Variscan (Permian) granites of south-west England are classic LCT granites, well-known for their tin and tungsten mineralisation. The surface outcrops are connected at depth to form the Cornubian Batholith⁹⁸, which is roughly 200 kilometres in length and includes biotite granites, tourmaline granites and topaz granites, and associated pegmatites. The main tin and tungsten mineralisation occurs as hydrothermally altered veins within the upper parts of the granites and their country rocks, and in late stage pegmatites and aplites. Columbite-tantalite and microlite have been recorded from the Meldon Aplite microgranite dyke, which intrudes Carboniferous country rocks on the north-western side of Dartmoor (von-Knorring and Condliffe, 1984). The relationship of this dyke to nearby granites is uncertain. Columbite-tantalite has also been found in pegmatites and topaz granites associated with the St Austell Granite, at Gunheath, Goonvean and Rostowrack clay pits (Symes, 2010, Scott *et al.*, 1998).

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- ⁹⁸ Batholith: a very large mass of igneous rock, tens to hundreds of kilometres across.

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This commodity profile was produced by the
British Geological Survey (2011).

It was compiled by Richard Shaw and
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This report is one of a series of Commodity Profiles
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