Niobium and tantalum: Geology, markets, and supply chains

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1. Introduction

Until 2014, niobium (Nb) and tantalum (Ta) were on the critical metals list of the European Union (European Commission, 2011; 2014). Both Ta and Nb have high levels of supply chain risk and even temporary disruptions in supply could be difficult to cope with. The Ta market is subject to influx of 'conflict' columbite-tantalite concentrate, or 'Coltan,' into the supply chain, displacing production in Australia and Canada. The growing consumer appetite for goods made of ethically sourced or 'conflict-free' minerals and metals has put pressure on manufacturers of components for consumer electronics, such as smart phones, laptop computers, computer hard drives, digital cameras, GPS navigation systems, and airbag triggers to stop using Ta from 'conflict' areas. Other uses of Ta include medical implants, super alloys used in jet turbine and rocket nozzle production, corrosion prevention in chemical and nuclear plants, as a sputtering target, and in optical lenses (Tantalum-Niobium International Study Center, 2015a, b). These applications make Ta economically and strategically important to industrialised countries (European Commission, 2011, 2014; Brown et al., 2012; Papp, 2012).

Niobium (Nb) is primarily used in high-strength low-alloy (HSLA) steel used extensively in the oil and gas and automotive industries. Niobium is also a major component in vacuum-grade alloys used in rocket components and other aeronautic applications (Tantalum-Niobium International Study Center, 2015a, c). Demand for Nb is increasing due to greater use of Nb in steel making in China, India, and Russia (Roskill, 2013b; Mackay and Simandl, 2014). Because most primary Nb production is restricted to a single country (Brazil), security of supply is considered at risk (European Commission, 2014). New sources of supply may be developed to diversify geographic location of supply for strategic reasons (Mackay and Simandl, 2014). Herein we summarize the geology, market, and supply chains of Niobium and Tantalum metals.

2. Geology of tantalum- and niobium-bearing deposits

This section considers the geology of pegmatite-related Ta deposits, peraluminous granite-related Ta ±Nb deposits, carbonatite-related Nb deposits, and peralkaline complex-hosted Nb-Ta-REE deposits. In near-surface environments, these primary deposits are commonly enriched by weathering and are also a source of placer deposits.

2.1. Pegmatite-related Ta deposits

Pegmatites are coarse-grained (most crystals >1 cm) igneous intrusive rocks found in a variety of tectonic and metamorphic settings. They form small (usually less than a metre thick and tens to hundreds of metres long) sills, dikes, and irregular pods and lenses (Jahns, 1955; Varlamoff, 1972; Černý, 1975, 1982). Exceptionally large pegmatite bodies (e.g. Greenbushes, Wodgina, and Tanco) can be tens of metres in thickness and extend along strike for kilometres. The main rock forming minerals in pegmatites are potassium feldspar, albite, and quartz ±muscovite and/or biotite (Černý, 1991a). Accessory mineralogy is occurrence specific with hundreds of exotic minerals in highly fractionated pegmatites (Černý, 1991a). Complete reviews of pegmatite mineralogy are provided by Černý and Ercit (1985), Černý (1991a), and Černý and Ercit (2005).

Pegmatites have been the subject of numerous detailed studies and genetic reviews (Ginsberg, 1984; Černý, 1982, 1991a, b; Černý and Ercit, 2005; and references therein). Of the five pegmatite classes based on geological environment and geochemistry (abyssal, muscovite, muscovite-rare-element, rare-element, and miarolitic; Černý and Ercit, 2005), the rare-element class is the most important for Ta exploration.

Pegmatites can also be classified into three petrogenetic families (Černý, 1991a; Černý and Ercit, 2005): 1) the LCT family (enriched in Li, Cs, and Ta); 2) the NYF family (enriched in Nb, Y, and F); and 3) the relatively rare mixed NYF+LCT family with overlapping mineralogical or chemical characteristics of the two previously mentioned families (Černý, 1991a; Černý and Ercit, 2005).

The LCT family shows petrogenetic affinity to peraluminous and metaluminous S-type rare-element enriched granites (Černý, 1991a, b; Černý and Ercit, 2005; Martin, 2007). These pegmatites mainly occur in orogenic settings and are associated

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with crustal shortening (Moloshag, 1974; Anhaeusser, 1976; Černý, 1982; Trueman and Černý, 1982; Möller and Morteani, 1983). Rare-element content (specifically Li, Cs, Be, Ta, and Nb), Ta:Nb ratio, and degree of albitization increase with distance from the source intrusion (Trueman and Černý, 1982; Černý, 1991b). LCT pegmatites are characterised by the presence of muscovite, garnet, tourmaline, and aluminosilicates (Černý and Ercit, 2005). Common Ta-bearing minerals are columbite-tantalite, microlite, wodginite, and euxenite (Hatcher and Bolitho, 1982; Trueman and Černý, 1982; Černý, 1991a; Hatcher and Clynick, 1990). Pegmatites hosting Ta deposits that have been exploited in the past (e.g. Wodgina and Greenbushes, Australia; Tanco, Canada; and Kenticha, Ethiopia) typically belong to the LCT family.

Pegmatites belonging to the NYF family are found mainly in continental anorogenic settings and show affinity to the fractionated portions of metaluminous A- and I-type granites (Černý, 1991a; Černý and Ercit, 2005). Pegmatitic phases of peralkaline and carbonatite complexes share many characteristics with NYF pegmatites (Martin and De Vito, 2005; Martin, 2007), and have the potential to be mineralized in Nb, REE, and other rare-elements (e.g. Strange Lake, Canada).

2.2. Peraluminous granite-related Ta ±Nb deposits

Rare-element-enriched peraluminous granites (Al_2O_3/$(CaO+Na_2O+K_2O)$>1; Shand, 1927; Clarke, 1981) can be enriched in Ta and Nb and are found in post-orogenic and orogenic tectonic settings (Pitcher, 1983, 1993; Barbarin, 1990; Lin et al., 1995; Linnen and Cuney, 2005). These granites are small vertically zones intrusions covering surface areas from 0.25 km^2 (Beauvoir granite; Raimbault et al., 1995) to about 2 km^2 (Orlovka; Reyf et al., 2000). Like pegmatites, mineralization is associated with increasing degree of fractionation (Černý and Meintzer, 1985; Breaks et al., 2003). Some occurrences have stockscheider and/or greisenized cupola containing quartz, muscovite, lepidolite, topaz, and commonly tourmaline, fluorite, wolframite, and cassiterite with accessory beryl or Ta- and Nb-bearing minerals (Černý and Meintzer, 1988; Johan and Johan, 1994; Lin et al., 1995; Linnen and Cuney, 2005). Characteristic rock forming minerals in rare-element-enriched granites include quartz, plagioclase, alkali feldspar, and accessory minerals such as biotite, muscovite, garnet, cordierite, staurolite, aluminosilicates, mullite, topaz, tourmaline, spinel, and corundum (Clarke, 1981). The Yichun granite in China (Lin et al., 1995; Papp, 2012), the Beauvoir granite in France (Raimbault et al., 1995), and the Orlovka granite in Russia (Seltmann et al., 2010) are examples of current or former Ta producers.

2.3. Carbonatite-related Nb deposits

Carbonatites are defined as igneous rocks containing more than 50% modal carbonate minerals and no more than 20 wt.% SiO_2 and are commonly subdivided by proportion of CaO, MgO, and $FeO+Fe_2O_3+MnO$ (Le Maitre, 2002). More elaborate classifications involving mineralogical and genetic concepts were developed by Woolley (2003), Mitchell (2005), and Woolley and Kjarsgaard (2008); these are not typically used by the exploration industry. Most carbonatites are found in extensional intracratonic tectonic settings and less commonly at cratonic margins (Woolley and Kjarsgaard, 2008). A few rare occurrences are found in oceanic settings. They form sills, dikes, plugs, or zoned complexes such as at St. Honoré (Thivierge et al., 1983; Lafleur and Ayad, 2012). Some carbonatites (specifically those found on cratonic margins) are complexly deformed (e.g. Upper Fir; Chong et al., 2012). Rarely, they form extrusive and pyroclastic aprons.

The composition of carbonate minerals in carbonatite complexes can range from calcite through dolomite to magnesite, siderite, and ankerite (Woolley, 2003; Mitchell, 2005; Woolley and Kjarsgaard, 2008). Carbonatites are commonly enriched in incompatible elements (Sr, Ba, Nb, REEs, and especially LREE) and are the main sources and exploration targets for Nb and LREEs (Mariano, 1989a, b; Richardson and Birkett, 1995; Birkett and Simandl, 1999). They may also host economic concentrations of U, Th, Ba, P, Zr, F, V, Fe, and possibly Ta. Many carbonatite complexes, such as St. Honoré, Canada, and Araxá, Brazil, are spatially associated with nepheline syenites or other alkaline silicate igneous rocks (Thivierge et al., 1983; Woolley, 2003; Mitchell, 2005; Woolley and Kjarsgaard, 2008; Lafleur and Ayad, 2012). Lunate, semi-circular, or concentric rock units are formed by successive phases of igneous intrusion, and common in carbonatite (Mitchell, 2005; Woolley and Kjarsgaard, 2008). Late stage carbothermal fluids may form a central brecciated REE-, Sr- and Ba-rich plug (Mitchell, 2005; Woolley and Kjarsgaard, 2008).

Alkali-rich hydrothermal fluids from carbonatite intrusions commonly produce envelopes of sodic or potassic alteration, or fenitization (Heinrich, 1985; Le Bas, 2008). The degree of fenitization decreases with distance from the carbonatite. Fenites can be macroscopically indistinguishable from alkaline igneous silicate rocks, intensely altered host rocks, and mildly brecciated or fractured rocks with veinlets of K, Na, and/or Fe minerals. Recognition of the fenitization zones increases the size of the carbonatite exploration target (Mackay and Simandl, 2014).

2.4. Peralkaline complex-hosted Nb-Ta-REE deposits

Peralkaline igneous rocks have an alumina saturation index $(K_2O+Na_2O)/Al_2O_3$>1 (Shand, 1927) and are commonly found in extensional anorogenic continental tectonic settings (Pitcher, 1983, 1993; Barbarin, 1990). All peralkaline intrusions are enriched in high field strength elements (HFSE), especially agpaitic intrusions with complex Zr–Ti–REE silicates such as eudialyte, mosandrite, and rinkite (Gerasimovskii, 1956; Sørensen, 1960, 1968). They are also characterized by sodic phases such as aegirine, reibeckite, arfvedsonite, and albite. Agpaitic intrusions can be broadly subdivided into two categories: 1) layered intrusions, which display rhythmic or microrhythmic layering (e.g., Nechalacho, Canada; Lovozero, Russia; and Ilímaussaq, Greenland); 2) intrusions characterized

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by HFSE enrichment in pegmatitic/stockscheider related cupola(s) or nearby NYF affinity pegmatite/aplite dikes (e.g. Strange Lake, Canada; Miller, 1986; Richardson and Birkett, 1995; Salvi and Williams-Jones, 1990; Martin, 2007; Sheard et al., 2012). Detailed description of these different styles of intrusion are beyond the scope of this paper (see detailed examples in Mackay and Simandl, 2014 and references therein).

2.5. Tantalum and niobium ore minerals

The most common Nb and Ta ore minerals are pyrochlore supergroup minerals, columbite-tantalite series minerals, struvereite, loparite, and euxenite. Mineral chemistry for the columbite-tantalite series (the main ore minerals for Ta) can be plotted on a Mn/(Mn+Fe) and Ta/(Ta+Nb) quadrilaterals (Fig. 1). Columbite from carbonatites have specific chemistry; they are Nb-rich, with Mn/(Mn+Fe) ≤ 0.25 and Ta/(Ta+Nb) ≤ 0.20 (Fig. 1; Mackay and Simandl, 2015). Columbite from peralkaline complexes plot along the $FeNb_2O_6$–$MnNb_2O_6$ join of the quadrilateral with Mn/(Mn+Fe) ≤ 0.65 and Ta/(Ta+Nb) ≤ 0.15. Columbite-tantalite series minerals from LCT pegmatites and peraluminous granites are not well constrained and slightly overlap with columbite-(Fe) from carbonatites. Minerals from carbonatites, peralkaline complexes, peraluminous granites, and LCT pegmatites display a slight compositional overlap.

Pyrochlore supergroup minerals from carbonatites occupy the pyrochlore field and extend slightly into the betafite and microlite fields (>35% Nb, <65% Ti, and <45% Ta) when plotted on a Nb-Ti-Ta ternary discrimination diagram (Fig. 2; Mackay and Simandl, 2015). A narrow zone parallel to the Nb-Ti join (>40% Nb, <60% Ti, and <10% Ta) defines the mineral chemistry of pyrochlore from peralkaline complexes. Pyrochlore supergroup minerals from LCT pegmatites occupy the microlite field (<90% Nb, ≤ 40% Ti, and >15% Ta). Pyrochlore from peraluminous granites display microlite chemistry following the Nb-Ta join, extending slightly into the pyrochlore field (<65% Nb, <10% Ti, and >35% Ta). Figures 1 and 2 illustrate how pyrochlore supergroup and tantalite-columbite series concentrates produced from carbonatites and peralkaline complexes have low Ta content relative to concentrates produced from LCT pegmatites and peraluminous granite. These figures, in conjunction with the current Ta and Nb concentrate pricing practices (see below), indicate that carbonatites and peralkaline complexes are unlikely to become sources of Ta in the foreseeable future.

3. Grade and tonnage of Ta and Nb deposits

The tonnage and grade of Ta and Nb deposits varies significantly (Fig. 3). The level of confidence for resource and reserve estimates from many deposits in South America and Africa is less than for well-defined deposits in North America and Australia. Information from many deposits in China and Russia are lacking and these deposits are not included in Figure 3.

Overall, the highest Ta_2O_5 grades (Fig. 3a) correspond to LCT pegmatites (e.g., Tanco; Wodgina; and Morrua), substantially higher (e.g., Tanco 0.2160% Ta_2O_5) than rare element-enriched peraluminous granites (e.g., Orlovka, 0.0147% Ta_2O_5; Beauvoir, 0.0120% Ta_2O_5) or carbonatite-hosted deposits (e.g., Upper Fir, 0.0191% Ta_2O_5). All the deposits, including pegmatites, can be further enriched by weathering (e.g., Greenbushes or Volta Grande). These high-grade deposits generally have relatively low tonnage compared to peralkaline deposits. Peralkaline complexes have the largest resource in terms of total tonnage (e.g. Ghurayyah, and the Aires prospect, Motzfeldt). These peralkaline complexes are in early to moderate stages of exploration; none produce Ta. The highest Nb_2O_5 grades and tonnages (Fig. 3b) correspond to weathering-enriched carbonatite complexes (e.g. Araxá, Catalão I and II, and Seis Lagos) followed by hard rock carbonatite-related deposits (e.g., Aley and St. Honoré). Peralkaline-related deposits also represent significant tonnage and Nb_2O_5 content (e.g. Lovozero and Nechalacho).

4. Markets and sources
4.1. Tantalum market

Since 1999, a substantial portion (~22%) of the Ta supply chain includes concentrate sourced in politically unstable regions of West Africa (Papp, 2015a). Central and East Africa accounts for ~64% of Ta production. Introduction of coltan and inexpensive artisanally mined concentrates have undercut prices and resulted in several major past producers (e.g., Wodgina, Australia) being placed on care and maintenance (Tantalum-Niobium International Study Center, 2015a). Production is currently suspended at the Kenticha mine (Ethiopia) during renovations and expansions (Tantalum Niobium International Study Center, 2015a; Elenilto Mining, 2015; Papp, 2015a).

Capacitor-grade powders accounted for 25% of Ta shipments to worldwide processors during 2009-2013, down from 40% during 2001-2008 (Tantalum-Niobium International Study Center, 2015a). In 2013, Ta-chemicals accounted for 15% of Ta production, 2% in Ta-carbide, 11% in Ta-ingot, 22% in mill products, and 21% in metallurgical powders and scrap.

Waste and scrap recycling accounted for 48% of United States Ta imports in 2014, while primary production accounted for the remaining 52% (Papp, 2015a). Up to 79% of primary Ta production is from mining, with 21% from Sn slags (Tantalum-Niobium International Study Center, 2015a). Historically, Sn slags have accounted for up to 40% of global Ta production (Schwartz et al., 1995). Cassiterite placer deposits in Thailand and Malaysia were mined for their Sn content while Ta_2O_5 derived from columbite-tantalite and Ta-Nb rutile (strüverite) was also recovered from these deposits (Hassan, 1994; Schwartz et al., 1995).

World production of Ta from mining (excluding production from Ta contained in Sn slags) for 2014 was roughly 1157 tonnes of metal content (Fig. 4; Papp, 2015a). World Ta production began to increasing in 1999. During the 1990s and early 2000s, the price of Ta_2O_5 concentrate was relatively stable, under US$100/kg. By the year 2000, an increase in demand and perceived shortfall and instability in supply caused spot prices
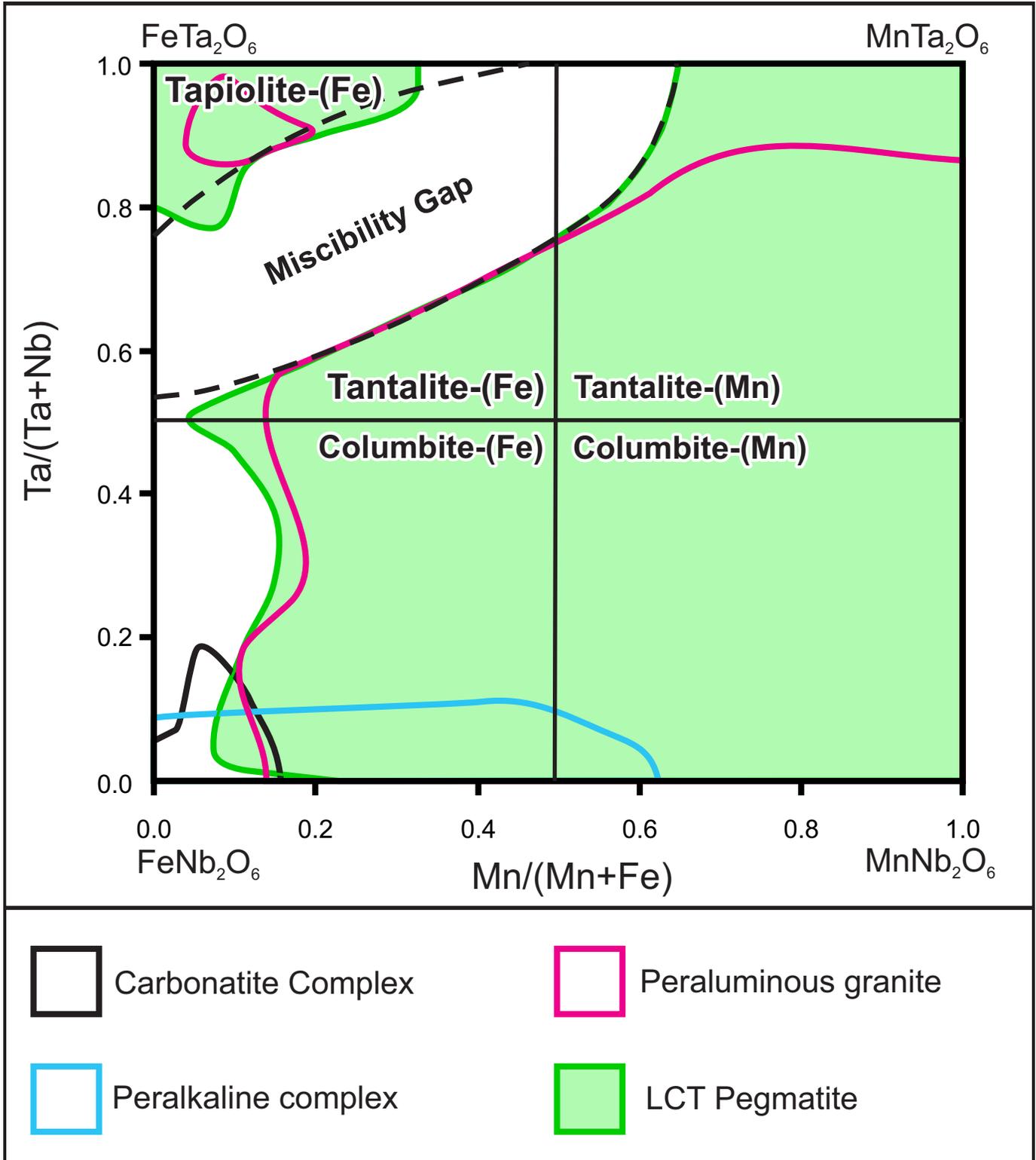
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Fig. 1. Composition of columbite-tantalite series minerals in carbonatites, peralkaline complexes, LCT pegmatites, and peraluminous granites. Modified from Mackay and Simandl (2015). Classification according to Černý and Ercit (1985, 1989).
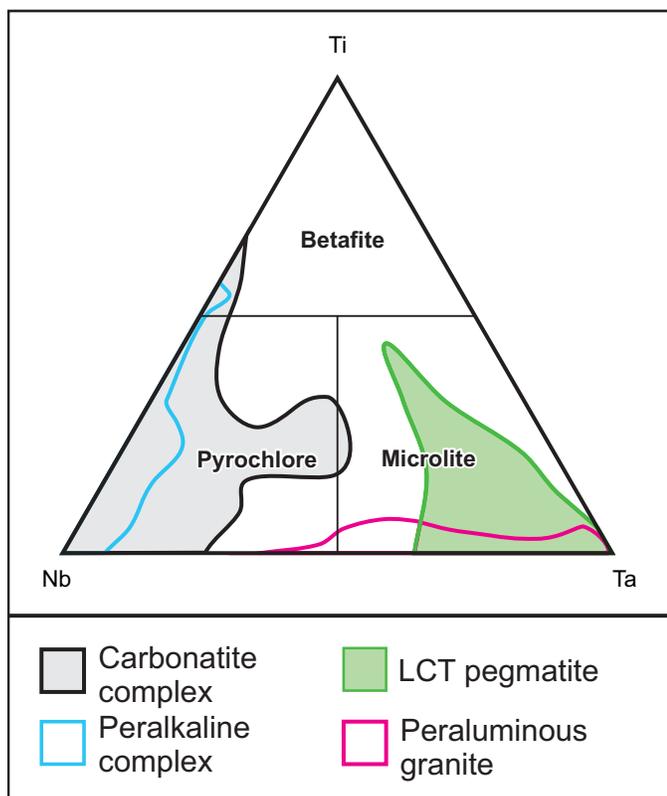
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Fig. 2. Compositional fields for pyrochlore supergroup minerals from carbonatites, peralkaline complexes, LCT pegmatites, and peraluminous granites. Modified from Mackay and Simandl (2015). Nomenclature of Atencio et al. 2010.

to spike to US$647/kg of contained Ta_2O_5 (Simandl, 2002). In response, production increased in the dominant supplier nation, Australia (Mackay and Simandl, 2014). Tantalum pentoxide prices had dropped and stabilized under US$120/kg by 2002. Prices again began to rise in 2010, peaking in 2011 at $275/kg and falling slightly to $242/kg in 2014 (Papp, 2015a). Higher Ta_2O_5 concentrate prices may be related to shortages of conflict-free concentrate, the high economic importance of Ta, and high supply risk (European Commission, 2011). Tantalum was recently removed from the critical metals list of the European Union. The supply risk for Ta remains elevated relative to other economically significant metals such as Cu or Fe (European Commission, 2014).

4.2. Tantalum sources

Lithium-cesium-tantalum (LCT) pegmatites and related weathered crusts, rare-element-enriched granites, and placer deposits account for most Ta production (Mackay and Simandl, 2014). Well known examples of LCT pegmatites that are, or were, historically mined for Ta include Greenbushes and Wodgina, Australia; Tanco, Canada; Keticha, Ethiopia; and Marropino, Mozambique (Mackay and Simandl, 2014). Other historical sources of Ta ores include peraluminous granites (e.g. Yichun, China, and Orlovka, Russia) and artisanally mined placers located in Rwanda, Congo, Burundi, and as a by-

product of Sn slag refining in Thailand and Malaysia (Simandl, 2002; Shaw and Goodenough, 2011; Papp, 2012; Pohl, 2012).

Currently, most Ta concentrates are produced artisanally from placer deposits in western and central Africa, the Mibra Mine, Volta Grande, and the Pitinga Mine (all in Brazil; ~8% of Ta production), and Marropino in Mozambique (Fig. 4). Tantalum production from Sn placer deposits in Thailand is not considered in Figure 4. The Pitinga deposit is hosted in a peralkaline unit within a predominantly peraluminous granite (Nardi et al., 2012; Horbe et al., 1991; Bastos Neto et al., 2009). The Yichun mine (China) is another well-known source of Ta, as well as Nb and Li (Lin et al., 1995; Papp, 2012), though production details are not reliably known (Mackay and Simandl, 2014). China accounts for ~5% of Ta production (Fig. 4; Papp, 2015a).

Infrastructure and permitting and, in some cases, mining and processing equipment are in place at most past-producing mines currently on care and maintenance. Favourable market conditions could see these mines reopen, giving them a head start and low starting cost advantage over grass roots Ta exploration projects. Pegmatites, rare-element-enriched peraluminous granites, their weathered equivalents, and placers remain the most favourable hosts for undiscovered economically significant Ta resources (Mackay and Simandl, 2014). Some carbonatite-hosted deposits are also promoted based on the recovery of Ta as a co-product of Nb, such as the Upper Fir (Chong et al., 2012) and Crevier (Duplessis and Girard, 2010) deposits in Canada.

4.3. Niobium market

The vast majority of primary Nb production, ~90%, comes from Brazil (Fig. 5). Any loss of Nb production in Brazil would drastically impact the economies of most modern industrialised nations. A few Nb deposits are on care and maintenance or have existing infrastructure and could be restarted quickly. Niobium co-production with other elements (such as REEs, Zr, and/or Y) from peralkaline complexes (e.g. Nechalacho and Strange Lake) is technically possible but unlikely under current REE market conditions.

In 2013, 88% of Nb was used to produce high-strength low-alloy (HSLA) steel (containing at most 0.1% Nb, commonly approximately 0.03% Nb) used extensively in high-pressure pipeline construction, offshore petroleum drilling platforms, and as major components in the automotive industry, with minor use of Nb in superconducting alloys (Roskill, 2013b; Tantalum-Niobium International Study Center, 2015). Only 4% of Nb was used in high-strength and corrosion resistant Nb-super alloys or vacuum-grade niobium alloys. These super alloys are essential for rocket and jet engine components used in the space and aviation industries (Papp, 2015b). The remaining Nb was used to produce Nb chemicals including catalysts (4%), pure Nb metal (3%), and as Nb alloys such as NbTi (1%) used in superconducting applications (Tantalum-Niobium International Study Center, 2015).

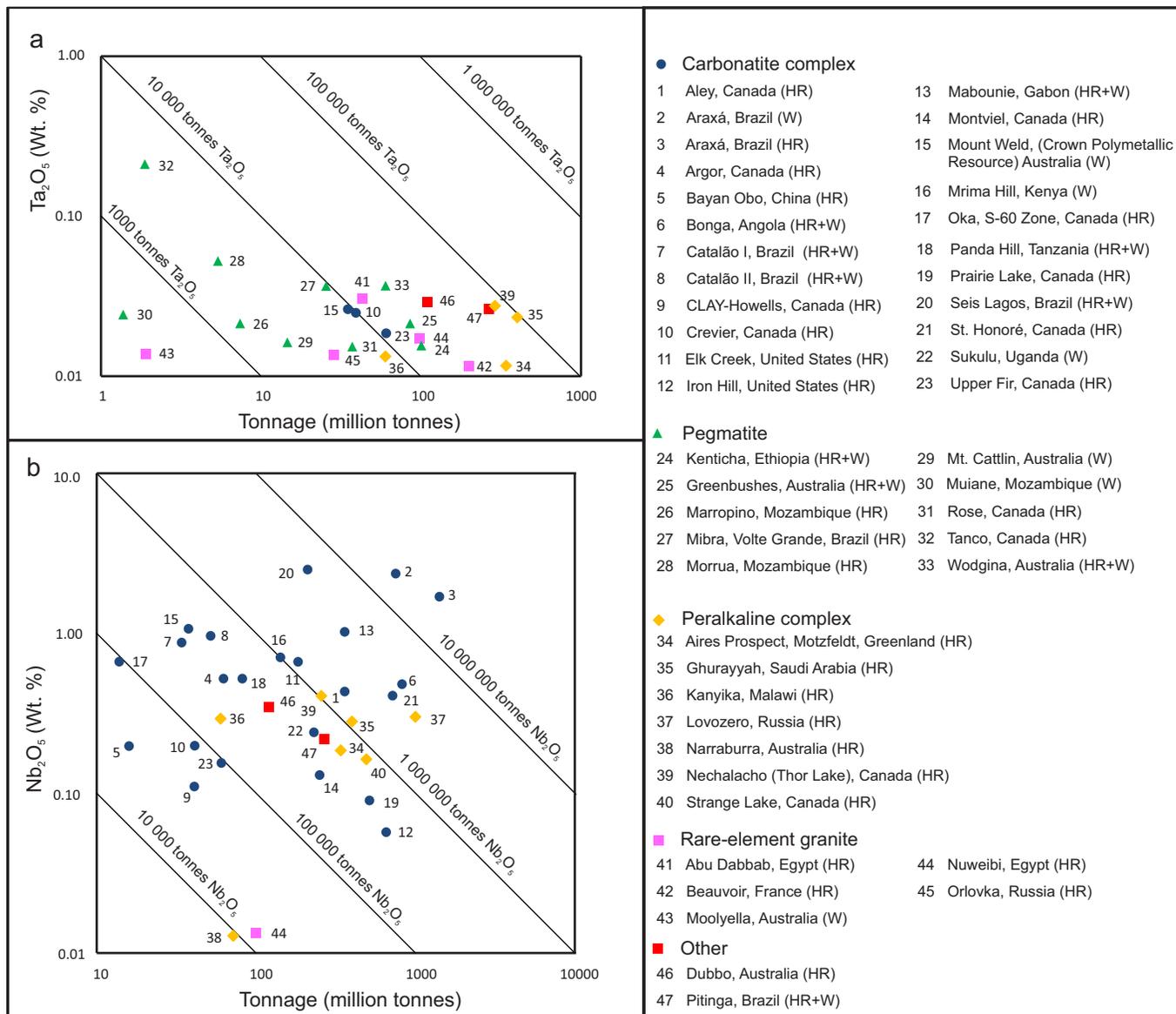The price of ferroniobium (Fe-Nb alloy containing 65%

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Fig. 3. Grades and tonnages of **a)** Ta and **b)** Nb deposits associated with carbonatite complexes, pegmatites, peralkaline complexes, and rare-element granites. Diagonal lines indicate tonnage of Ta_2O_5 and Nb_2O_5. Modified from Mackay and Simandl (2014). Grade and tonnage references are available in Mackay and Simandl (2014) and in updates based on Gippsland (2015a, b), Vallieres et al. (2013), Anglo American PLC (2015), and Pittuck et al. (2015). Abbreviations: (HR) hard rock ore, (W) weathered ore, (HR+W) hard rock and weathered ore combined.

Nb_2O_5) began to rise rapidly in 2006 (Mackay and Simandl, 2014). Higher prices since 2006 coincide with increased production, indicating a growing demand for Nb in HSLA steel worldwide. Prices peaked at 43,658 US$/tonne of ferroniobium in 2012 and fell slightly to 42,000 in 2014 (Papp, 2015b).

Mine production of Nb has increased rapidly over the last 15 years, from 18,323 tonnes of contained Nb in 1994 to 59000 tonnes in 2014, down slightly from 68,700 tonnes in 2013 (Fig. 5; Papp, 2015b). In 2013, about 20% of Nb was sourced from recycled material (Tantalum-Niobium International Study Center, 2015). Currently, steel production in the USA, Japan, South Korea, Brazil, and EU uses higher concentrations of Nb than China, India, and Russia (Roskill, 2013a). Demand

for Nb will likely continue to rise until concentrations of Nb in Chinese, Indian, and Russian steel reach the same levels as those in the EU and United States.

4.4. Niobium sources

The main Nb producers in Brazil, the Araxá and Catalão I and II carbonatites, account for about 90% of Nb mine production. Outside of Brazil, the St. Honoré carbonatite (Canada) accounts for most of the remaining global Nb production (~8%), with a small portion (~2%) sourced from loparite concentrate from the Lovozero peralkaline complex (Russia; Papp, 2015b). Niobium is predominantly derived from weathering-enriched material associated with carbonatite complexes (e.g. Araxá and
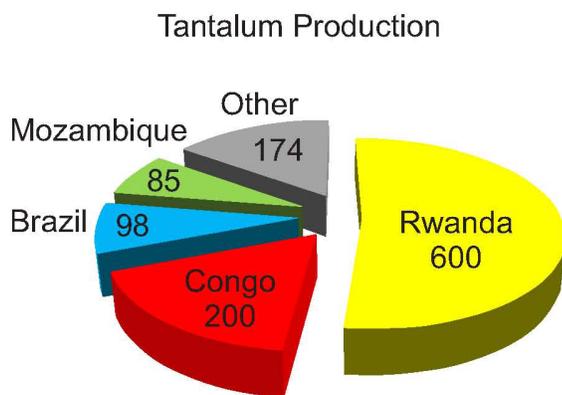
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Tantalum Production

Fig. 4. World mine production (metric tonnes) of contained Ta metal (excluding Ta recovered as a by-product of Sn mining) by country in 2014. Values for Rwanda and Congo updated on May 14, 2015. "Other" includes China (60), Nigeria (60), Ethiopia (40), Burundi (14). Data from Papp (2015a).
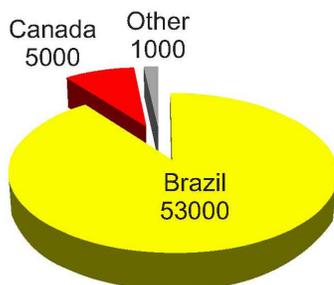
Niobium Production

Fig. 5. World mine production of contained Nb metal by country from 2014. Data compiled from Papp (2015b).

Catalão I and II, Brazil; Mackay and Simandl, 2014). Niobium ore is rarely produced from unweathered carbonatite deposits (e.g. St. Honoré and historically Oka, Canada).

Future co-production of Nb with REEs is being considered at several carbonatite complexes such as St. Honoré (Ciuculescu et al., 2013), and Iron Hill, United States (Staatz et al., 1979; v. Gosen, 2009). Similarly, co-production of Nb with phosphate may increase economic viability at deposits such as Prairie Lake, Canada (Nuinsco Resources Ltd., 2014); Nkombway Hill, Zambia (v. Straaten, 2002); and Sukulu, Uganda (Karagambe-Kaliiza, 1989). There is potential for co-production of Nb with other metals (REEs, Y, and/or Zr) in peralkaline deposits such as Nechalacho, Canada (Ciuculescu et al., 2013); Strange Lake, Canada (Gowans et al., 2013); Kipawa, Canada (Saucier et al., 2013); Lovozero, Russia (Zaitsev et al., 1998); and Motzfeldt, Greenland.

4.5. Ta and Nb concentrate pricing considerations

The Nb and Ta markets are limited. Prices of Ta and Nb concentrates are set for each contract by negotiations between buyers and sellers. Tantalite concentrates are expected to contain more than 30% Ta_2O_5 (Tantalum-Niobium International Study Center, 2013a). Concentrates with a minimum content of 20% Ta_2O_5 may also be considered. The value of concentrate is based on Ta_2O_5 content; Nb_2O_5 is commonly ignored. The price for Nb concentrate with low Ta_2O_5 content is determined by summation of Nb_2O_5+Ta_2O_5 content and valuation is based on the price for Nb_2O_5. The higher value of Ta_2O_5 relative to Nb_2O_5 is ignored (Tantalum-Niobium International Study Center, 2013a, b). When sold for production of ferroniobium Ta is ignored, as it cannot be removed. Additionally, some Ta and Nb concentrates may have non-negligible U and Th content. High concentrations of these elements require extra health and environmental precautions during mining, concentrate transportation, and processing (Tantalum-Niobium International Study Center, 2013a, b).

Multiple co-products are perceived to insulate a project from economic downturns as REE, Nb, Ta, and Zr are used in different products. However, complex metallurgy commonly results in high capital and plant operating costs (Mackay and Simandl, 2014). The potential for Nb recovery as a co-product of Zr and REE from peralkaline complexes is determined to a large extent by the mineralogy, mineral chemistry, texture, and particle size and is deposit specific as illustrated by Nechalacho (Ciuculescu et al., 2013), Kipawa (Saucier et al., 2013), and Lovozero (Zaitsev et al., 1998). Metallurgical aspects of Ta and Nb deposits are covered in detail by Shaw and Goodenough (2011) and Linnen et al. (2014).

5. Summary

Tantalum availability, in the short to medium term, may be affected by increasing resistance to use of conflict materials. Pegmatites, peraluminous granites, weathered crusts, and placers account for most primary Ta production. Slag refining of Sn placer deposits currently accounts for approximately 21% of Ta production; recycling accounts for 48% of the supply chain. Should the gap in Ta availability persist, large-scale mechanized mining of pegmatite-hosted Ta-bearing deposits, such as at Greenbushes and Wodgina (Australia), which are currently on care-and-maintenance, are likely to return into production. Niobium is high on the critical metals list of the European Commission critical metals report for the EU, largely because 90% of primary Nb production is geographically restricted to a single country (Brazil). Most of the balance (~8%) comes from the St. Honoré carbonatite (Canada). A small portion (~2%) of Nb production is from loparite concentrate from the Lovozero peralkaline complex (Russia).

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