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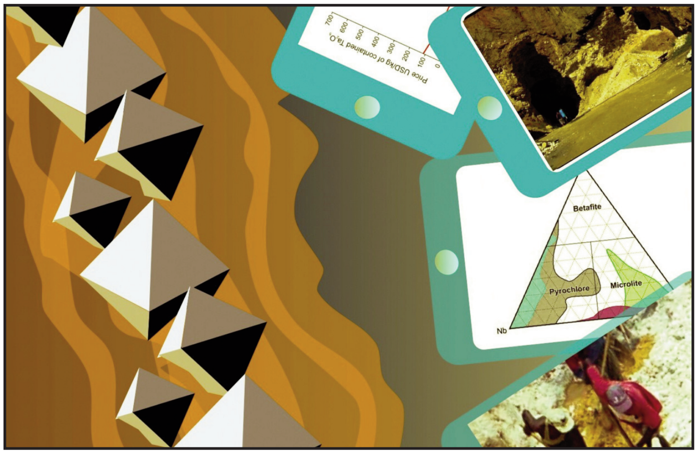

Economic Geology Models 4. Tantalum and Niobium: Deposits, Resources, Exploration Methods and Market – A Primer for Geoscientists

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SUMMARY

The world's main tantalum (Ta) resources are in pegmatites (e.g. Wodgina, Australia), rare element-enriched granites (e.g. Abu Dabbab, Egypt), peralkaline complexes (e.g. Nechalacho, Canada), weathered crusts overlying the previously mentioned deposit types, and in placers. Niobium (Nb) resources with the highest economic potential are in weathered crusts that overlie carbonatite complexes (e.g. Catalão I and II, Brazil). Brazil accounts for 90% of the global Nb mine production with another 9% coming from the Niobec Mine, Canada (a hard-rock underground mine). However, at least 17 undeveloped carbonatite complexes outside of Brazil have NI-43-101 compliant Nb resource estimates (e.g. Aley carbonatite, Canada). Concentrates from most carbonatites are used to produce ferroniobium (Fe–Nb alloy), and Ta is not recovered. The Ta and Nb contents of some carbonatites (e.g. Upper Fir deposit and Crevier dyke, Canada) are of the same order of magnitude as that of pegmatite ores; however, concentrates from carbonatites have a higher Nb/Ta ratio. Historically, 10–12% Ta_2O_5 in Nb concentrates has not been recovered in 'western' smelters because of the hydrofluoric acid cost. Western countries perceive Ta and Nb supplies to be at risk. Tantalum market downturns resulted in several mines in Australia and Canada closing, at least temporarily, and a resultant shortfall has been filled by what is now recognized as 'conflict-free columbite-tantalite' from Central Africa. The lack of ore will not be a key factor in future Ta and Nb supply disruption. For example, more than 280 Nb- and 160 Ta-bearing occurrences are known in Canada alone, and more resources will likely to be discovered as geophysical and geochemical exploration methods are optimized.

RÉSUMÉ

Les principales sources mondiales en tantale (Ta) sont les pegmatites (par ex. Wodgina, Australie), les granites enrichis en éléments rares (par ex. Abu Dabbab, Égypte), les complexes hyperalcalins (par ex. Nechalacho, Canada), les croûtes altérées recouvrant les types de gisements déjà mentionnés, et les placers. Les sources en niobium (Nb) ayant le meilleur potentiel économique se trouvent dans les croûtes altérées qui recouvrent les complexes de carbonatite (par ex. Catalão I et II, Brésil). Le Brésil est la source de 90% de la production minière mondiale de Nb, et 9% provient de la mine Niobec, au Canada (une mine souterraine). Cela dit, il existe au moins 17 complexes de carbonatite non développés à l'extérieur du Brésil dont les estimations de ressources en Nb sont conformes à la norme NI-43-101 (par ex. Aley carbonatite, Canada). Les concentrés de la plupart des carbonatites sont utilisés pour produire du ferroniobium (alliage Fe-Nb), et le Ta n'est pas récupéré. Les teneurs en Ta et Nb de certaines carbonatites

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(par ex. le gisement de Upper Fir et le dyke Crevier, Canada) sont du même ordre de grandeur que celles des minerais de pegmatite; cependant, les concentrés de carbonatites ont une proportion Nb/Ta plus élevée. Historiquement, 10 à 12% du Ta_2O_5 des concentrés de Nb n'ont pas été récupérés dans les fonderies de l'Ouest en raison du coût de l'acide fluorhydrique. Les pays occidentaux estiment que les approvisionnements en Ta et Nb sont à risque. Le fléchissement du marché du tantale a entraîné la fermeture, au moins temporaire, de plusieurs mines en Australie et au Canada, et la pénurie qui en résulte a été comblée par ce qui est maintenant reconnu comme étant du minerai de colombite-tantalite «sans conflit» d'Afrique centrale. Le manque de minerai ne sera pas un facteur clé des perturbations à venir de l'approvisionnement en Ta et Nb. Par exemple, plus de 280 occurrences minérales contenant du Nb et 160 occurrences minérales contenant du Ta sont connues au Canada seulement, et davantage de ressources seront probablement découvertes à mesure que les méthodes d'exploration géophysique et géochimique seront optimisées.

Traduit par le Traducteur

INTRODUCTION

Tantalum (Ta) is used largely in capacitors for automotive electronics, mobile phones, and personal computers, as well as in glass lenses, and as Ta-carbide in cutting tools. The main uses of niobium (Nb) are High-Strength Low-Alloy (HSLA) steels and super alloys for the aerospace industry (Roskill Information Services 2016).

Tantalum and Nb are commonly considered strategic and critical materials in modern society (Simandl et al. 2015, and references therein). However, lists of critical materials vary to a large extent on the priorities and objectives of the organization that commissions the study (Simandl et al. 2015, and references therein). For example, both Ta and Nb are considered critical by the most recent assessment ordered by the European Commission (2017). The level of criticality of an assessed commodity is based on a combination of: 1) its importance to the economy of the European Union, and 2) an estimate of the level of risk associated with their supply chain. To quantify supply risk, the European Commission relied on the World Governance Indicator (WGI). The WGI includes factors such as voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption (European Commission 2017). Tantalum and Nb are also on the newest criticality list in United States of America (USGS 2018).

In general, projects involving critical materials are popular with investors. Niobium and Ta grade, the Ta_2O_5/ [Ta_2O_5 + Nb_2O_5] ratio of the concentrate, tonnage, mineralogy, and permissive metallurgy are some of the key technical factors that are used to screen and rank potential development projects. However, since Ta and Nb are considered strategic for the economy and national security of many industrialized countries, governmental interventions will perturb any project ranking based strictly on technical and economic parameters.

OVERVIEW OF GEOLOGY OF Nb AND Ta DEPOSITS

The world's main primary Ta resources are contained in pegmatite-related deposits (e.g. Wodgina: Li, Ta, Australia; Mibra: Ta, feldspar, Sn, Brazil; and the historic but now depleted Tanco deposit: Ta, Cs, Li, Canada); rare element-enriched granites (e.g. Yichun, China; Beauvoir, France), and in peralkaline granite complexes (e.g. Nechalacho: REE, Nb, Ta, Zr, Canada; Al Ghurayyah: Ta, Nb, Saudi Arabia). Important resources also exist in weathered crusts overlying the previously mentioned hard-rock deposit types, and in placer deposits where Ta may be a co-product of tin (Mackay and Simandl 2014a; Linnen et al. 2014; Burt 2016). Weathered crusts are preferred to hard-rock deposits because weathering liberates Ta-bearing minerals and no blasting, crushing or grinding are required. In this respect, Ta production from weathered crusts differs from the processing of similar materials for Nb extraction (see below).

Globally, most Nb resources are contained in carbonatite complex-related deposits (e.g. Catalão I and II and Araxá, Brazil; Aley carbonatite and Niobec Mine, Canada) and peralkaline intrusions where Nb commonly coexists with rare earth element (REE) mineralization (Simandl 2014; Mackay and Simandl 2014a). Because of high grades and relatively simple metallurgy, most of the current Nb production comes from carbonatite complex-related deposits, notably where weathered zones are well developed. The pegmatitic body within the Lovozero peralkaline intrusion in the Kola Peninsula, Russia, is an exception. An estimated six thousand tonnes of loparite $[(REE,Na,Ca)_2(Ti,Nb)_2O_6]$ concentrate containing 30–35% REE_2O_3, 8–12% Nb_2O_5 and 0.6–0.8% Ta_2O_5 (Zaitsev and Kogarko 2012; Simandl 2014) are produced per year, with light REE being the main product. As with Ta deposits, intense and prolonged weathering of hard-rock carbonatite complex-related deposits has increased the Nb grade and reduced mining and processing costs.

In this review, only carbonatite-related Nb deposits and pegmatite-related Ta deposits are described, because these are the most important deposit types. These two deposit types currently supply the bulk of the world's Ta and Nb requirements. For information on the remaining types of Nb and Ta mineralization listed above, readers are referred to reviews by Linnen et al. (2014) and Mackay and Simandl (2014a).

Carbonatite-Related Nb (± Ta) Deposits

Carbonatites are defined by the International Union of Geological Sciences (IUGS) as igneous rocks containing more than 50% modal primary carbonates (Le Maitre 2002); however, they may have a metasomatic component. Most carbonatites are spatially associated with one or more of seven intrusive silicate rock groups, including melilitolites, ijolites, alkali gabbros, feldspathoidal syenites, syenites, kimberlites, and lamprophyres and/or their volcanic equivalents (Woolley and Kjarsgaard 2008). This association of rock types is referred to by the general term 'carbonatite complexes' or 'alkaline-carbonatite complexes'.

Figure 1. Well-formed pyrochlore crystal from the Ta–Nb-bearing Upper Fir carbonatite deposit, British Columbia, Canada.

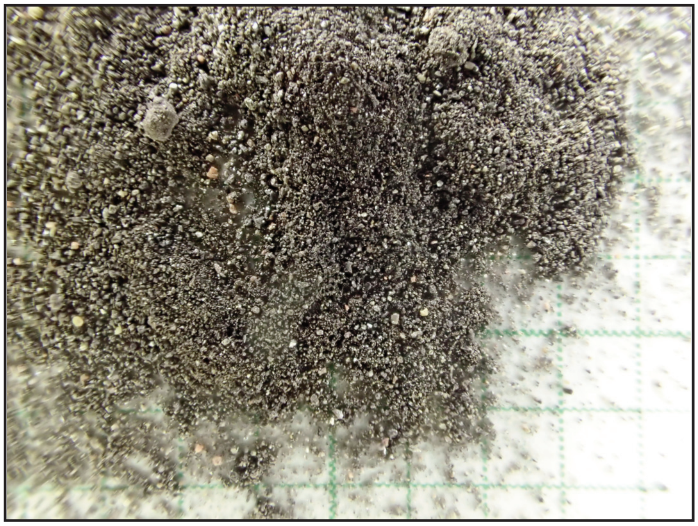

Figure 2. Pyrochlore concentrate from the Niobec Mine, St. Honoré carbonatite complex, Québec, Canada. Smallest visible squares on the underlying graph paper are 2 mm in size.

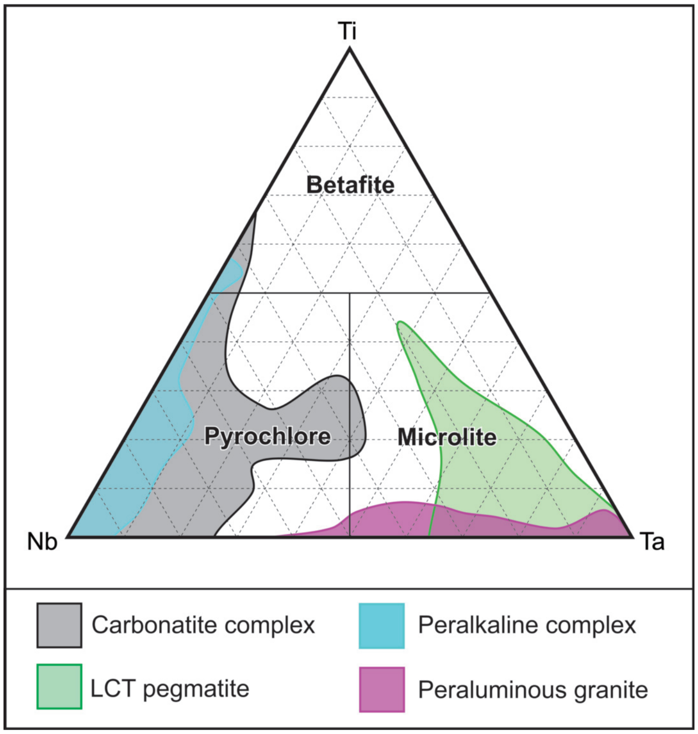

Figure 3. Compositional classification of pyrochlore supergroup minerals based on Ta, Nb, and Ti content. Pyrochlore, betafite, and microlite fields as defined by Atencio et al. (2010). Fields of pyrochlore compositions corresponding to carbonatite complexes, peraluminous granites, lithium–cesium–tantalum (LCT) pegmatites, and peralkaline complexes are from Mackay and Simandl (2015).

The Nb resources with the highest economic potential are in weathered crusts that overlie carbonatite complexes (e.g. Catalão I and II and Araxá, Brazil). Brazilian carbonatite complexes (weathered and fresh) account for approximately 90% of global Nb mine production, with another 9% coming from the Niobec Mine (a hard-rock underground mine operation) hosted by the St. Honoré carbonatite complex in Québec, Canada (Papp 2017a).

Niobium concentrates from most carbonatite-related deposits are dominated by minerals belonging to the pyrochlore supergroup (Figs. 1 and 2) as defined by Atencio et al. (2010). The composition of three end members may be approximated as follows: pyrochlore [$(Na,Ca)_2Nb_2O_6(OH,F)$]; betafite [$(Ca,U)_2(Ti,Nb,Ta)_2O_6(OH)$]; and microlite [$(Na,Ca)_2Ta_2O_6(O,OH,F)$]. Of these minerals, pyrochlore has the highest Nb content, and microlite has the highest Ta content, whereas betafite is enriched in Ti. Pyrochlore, which is characterized by high Nb and low Ta content (Fig. 3) typifies most carbonatite-derived pyrochlores (Mackay and Simandl 2015; Mackay et al. 2016).

Other common Nb (±Ta) minerals found in carbonatite-related mineralization are columbite-Fe [$(Fe,Mn)Nb_2O_6$], which forms an end member of the solid solution series with tantalite [$(Fe,Mn)Ta_2O_6$], fersmite [$(Ca,Ce,Na)(Nb,Ta,Ti)_2(O,OH,F)_6$] and to a much lesser extent Nb-rich rutile [$(Ti,Nb,Fe)O_2$] commonly referred to as ilmenorutile (Mackay and Simandl 2014a). Carbonatite-derived Nb concentrates are mainly used to produce ferroniobium and the associated Ta is not recovered.

In some cases, carbonatites are considered and assessed for Ta and Nb co-production. Examples in Canada include the Upper Fir deposit (indicated resource of 48.4 million tonnes grading 197 ppm Ta_2O_5 and 1,610 ppm Nb_2O_5) and the alkaline pegmatitic dyke within the Crevier carbonatite-syenite complex (indicated and measured resources of 25,369,000 tonnes at 0.2% Nb_2O_5 and 0.0234% Ta_2O_5 using the 0.1% Nb_2O_5 cut-off) (Simandl 2002; Simandl et al. 2002; SGS Canada Inc–Geostat 2010; Groulier et al. 2014; Kulla and Hardy 2015). In such cases, pyrochlore may have higher Ta content that approaches or reaches the pyrochlore–microlite boundary (Hogarth 1989; Simandl et al. 2002; Chudy 2014; Mackay and Simandl 2015). Such Ta-rich pyrochlores may have higher U content than their Nb-rich equivalents as supported by a positive correlation between Ta and U, and a negative correlation between Nb and U (Hogarth et al. 2000). The Ta_2O_5 content of mineralization in the Upper Fir and Crevier examples is of the same order of magnitude as that of pegmatite-related deposits from which Ta is being recovered; however, ore mineral concentrates from carbonatite-related deposits have lower $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$ ratios than those from pegmatites. Historically, Ta has not been recovered from concentrates containing less than 8 to 12% Ta_2O_5 or those having lower Ta content (Roethe 1989) because the cost of reagents (commonly hydrofluoric acid) exceeds the value of produced Ta and Nb metals in European and North American facilities. The $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$ ratios derived from resource calculations for the Upper Fir Carbonatite and Crevier intrusion are 0.122 and 0.117, respectively, suggesting that the Ta_2O_5 content of corresponding concentrates could be of the order of 6 to 8% Ta_2O_5. This implies that under current market conditions the concept of Ta metal recovery from carbonatite-derived Nb–Ta concentrate may not be realistic unless new and unconventional extraction methods are developed.

Pegmatite-Related Ta Deposits

For the purpose of this paper, our definition of pegmatite follows very closely the one provided by Neuendorf et al. (2005). Pegmatites are defined as exceptionally coarse-grained igneous rocks (individual crystals ≥ 1 cm in size) with interlocking grains. Pegmatites are usually found as irregular dikes, lenses, pods or veins within or near the margins of batholiths, plutons, or in surrounding country rocks. They commonly occur in clusters forming pegmatite fields. The chemical composition of pegmatites approaches that of granite and individual pegmatite bodies may be simple or complexly zoned. For a more comprehensive review of pegmatites, the reader is referred to London (2008). Pegmatites are commonly associated with aplites (related rocks with fine-grained allotriomorphic texture consisting predominantly of anhedral, equant grains). The complex relationship between pegmatites and aplites (massive and layered) is reviewed by London (2014). Tantalum mineralization may be present in both textural varieties but it is most commonly present in fine-grained (aplitic) rocks.

Pegmatites are subdivided into 'abyssal', 'muscovite', 'muscovite-rare-element', 'rare-element', and 'miarolitic' classes, all of which contain Ta–Nb–Sn minerals (Černý and Ercit 2005; London 2008; Simmons and Webber 2008). The 'rare-element' class is strongly enriched in high-field-strength elements (HFSE; e.g. Ta, Nb, Zr, Hf, P) and large-ion lithophile elements (LILE; e.g. Rb, Cs, Li, and Sr). This class of pegmatite has the best exploration potential for Ta. The subdivision of individual classes into subclasses, types, and subtypes is provided and further discussed by Černý et al. (2012).

Most granitic pegmatites, including those belonging to the 'rare-element class', may also be subdivided into two distinct families according to trace element signatures (Černý et al. 2012). These two families are either strongly enriched in lithium, cesium, and tantalum (LCT) or enriched in niobium, yttrium, and fluorine (NYF). Pegmatites of the 'rare-element class' that also belong to the LCT family are of the most interest to explorers looking for Ta, Li, and Cs. They have a chemical affinity with S-type rare-element enriched granites (Černý and Ercit 2005), occur in orogenic settings, and are associated with crustal shortening. They are commonly found adjacent to granitic cupolas or aligned along deep faults (Trueman and Černý 1982). Within the same pegmatite field, the Li, Cs, Be, Ta and Nb content, Ta/Nb ratio, and degree of albitization increase with distance from the parent intrusion (Trueman and Černý 1982). Tantalum enrichment is reflected by Ta-rich oxides and columbite-tantalite series minerals (Černý et al. 2012). Good examples of highly evolved LCT family pegmatites, also belonging to the 'rare-element class' are the famous Tanco pegmatite, which historically supplied concentrates of Ta-bearing minerals, spodumene, and pollucite $[(Cs,Na)_2Al_2Si_4O_{12}\ 2H_2O]$ and the Brazilian Urubu pollucite-bearing pegmatite (Fig. 4), which was a historical mica and gemstone producer.

Figure 4. Artisanal mine workings in the pollucite-bearing Urubu pegmatite, Brazil.

In contrast, mineralization in the NYF family of pegmatites is characterized by oxides and silicates containing heavy rare earth elements (HREE), Ti, U, Th, high concentrations of Nb relative to Ta, and abundant fluorine-bearing minerals (fluorite or topaz). From a practical point of view, the mineralization in these pegmatites is subject to the same metallurgical constraints as that of mineralization from peralkaline intrusions, described below.

Concentrates from most pegmatite-related Ta deposits (both hard-rock and weathered varieties) are dominated by minerals belonging to the columbite-tantalite series (Fig. 5); however, tapiolite $[(Fe,Mn)(Ta,Nb)_2O_6]$, wodginite $[Mn(Sn,Ta)(Ta,Nb)_2O_8]$, ixiolite $[(Ta,Nb,Sn,Mn,Fe)O_2]$ and pyrochlore supergroup minerals may be present in smaller amounts (Melcher et al. 2015, 2017). The wide compositional variation of minerals belonging to the columbite-tantalite series derived from pegmatites is shown in Figure 6. The field of columbite-tantalite series minerals from pegmatites covers most of the quadrilateral diagram and nearly coincides with that from peraluminous granites. In contrast to columbite-tantalite series minerals derived from carbonatites, those derived from carbonatites are chemically constrained to a small compositional field

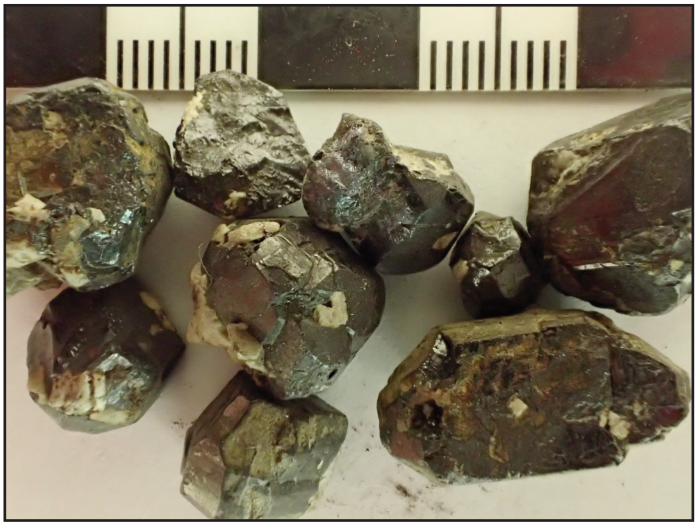

Figure 5. Pegmatite-derived columbite-tantalite series mineral from a pegmatite in Pilbara district, Australia. Sample from the School of Earth and Ocean Sciences (SEOS) mineral collection at the University of Victoria, British Columbia, Canada. Large division on the scale is 1 centimetre.

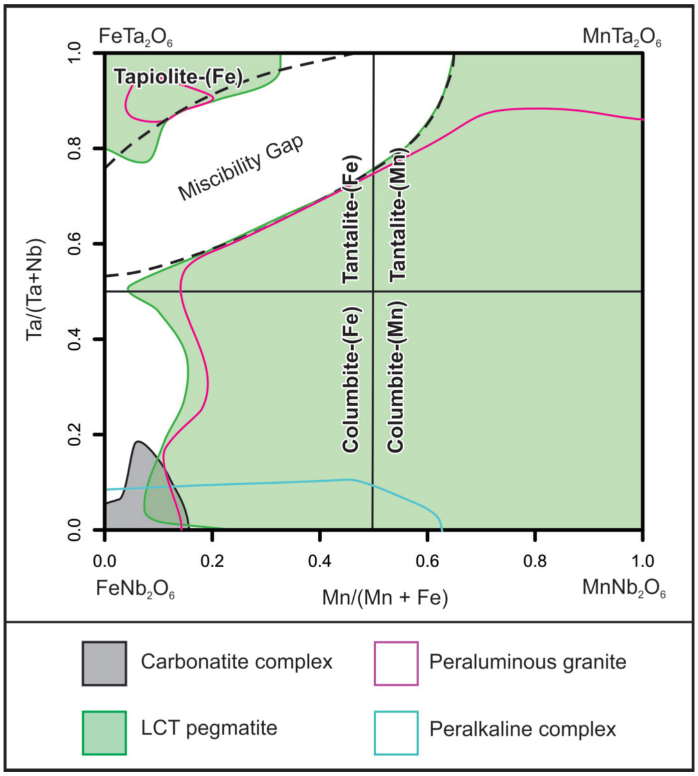

Figure 6. Quadrilateral diagram showing the variability in composition of columbite-tantalite series minerals (from Černý and Ercit 1985). The empirically derived tantalite-tapiolite miscibility gap is from Černý et al. (1992). Compositional fields for columbite-tantalite series minerals from carbonatite complexes, peraluminous granites, lithium–cesium–tantalum (LCT) pegmatites, and peralkaline complexes are from Mackay and Simandl (2015).

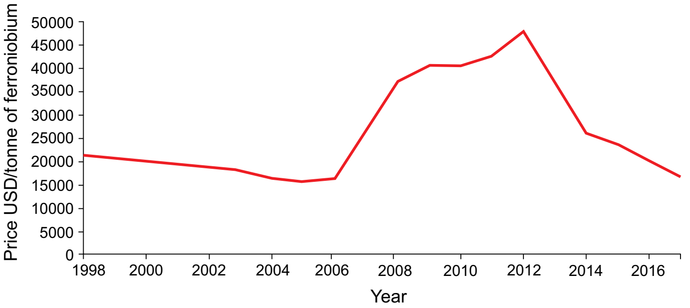

Figure 7. Historic mass-weighted average US import value of ferroniobium (assuming 65% Nb) for the period 1998 to 2018. Updated from Mackay and Simandl (2014a) based on information contained in US Geological Survey commodity summaries. Prices are adjusted for inflation to 2012 US dollars.

adjacent to the columbite-(Fe) apex with low Ta content. Columbite-tantalite series minerals derived from peralkaline intrusions also have a low Ta content; however, their Mn/(Mn+Fe) ratio is less constrained (Fig. 6). In the ranking of Ta exploration projects for potential development, all other parameters being equal, the higher the $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$ ratio of the deposit, the better its chance of being developed.

NIOBIUM AND TANTALUM SUPPLY CHAINS

The fundamentals of the Nb supply chain have not changed significantly during the last 20 years. More than 90% of the world's Nb production is restricted to a single South American country, Brazil. Worldwide, all major producing Nb mines are highly mechanized and with the exception of the Niobec Mine (St. Honoré complex, Québec, Canada), they are exploited by opencast mining. The world mine production for 2017 was approximately 64,000 tonnes of Nb content (Polyak 2018a). Some important changes that took place in Brazil were linked to more than a fivefold increase in the cost of hydroelectricity from $25.80 per megawatt-hour to $147.38 per megawatt-hour in 2015 (Papp 2017c). These price hikes were attributed to the worst drought in 80 years, and the increased energy costs had a significant impact on production costs. Traditionally, most of the Nb product was sold in the form of ferroniobium (rather than concentrate consisting of Nb-bearing minerals) and produced by vertically integrated companies. Consequently, ferroniobium prices are relatively insensitive to global demand (Fig. 7) if compared to other commodities. For example, the 2008–2009 slump in demand had a minimal impact on Nb pricing. The 2016 sale of Anglo American's Nb and phosphate operations in Brazil to China Molybdenum Co., Ltd. also did not appear to have a major impact on the Nb market; however, since that sale, a larger proportion of concentrate may be shipped to Asia to be transformed into ferroniobium. Despite Nb being considered a critical metal, unless political instability develops in Brazil, any change to the Nb supply chain is expected to be gradual. It remains to be seen if and when some of the more advanced Nb projects outside of Brazil will reach production stage.

In contrast to Nb, the fundamentals of the Ta supply chain have changed dramatically during the last ten years. As recently as 2007, mechanized mining and processing operations, such as Greenbushes and Wodgina in Australia, Tanco in Canada, and mines in Brazil, China, Ethiopia, and Mozambique (Fig. 8), were producing approximately 75% of the world's Ta in concentrates, with artisanal production accounting for the rest,

Figure 8. Original (circa 2004) industrial-scale processing plant (spiral module 1) at Marropino, Mozambique. The Marropino pegmatite, which was at one time considered as the second largest Ta producing deposit is also well known for gem-quality morganite (pink beryl).

either as columbite-tantalite (colloquially known as 'coltan') or as a co-product of tin mining. However, the 2008 stock market meltdown and the mini-recession that followed resulted in a decline in the demand for Ta and lower prices, forcing several of the higher-cost industrial mines off the market, at least temporarily and subsequently forcing increased reliance on generally lower-cost artisanal mines. Notwithstanding a spike in prices from 2010 to 2012, both large Australian mines (Greenbushes and Wodgina) remain closed, at least temporarily, and Tanco has ceased mining Ta ore at its underground mine in Canada. Mechanized mines in Brazil, Ethiopia, Mozambique, China, as well as some new producers in Australia and one in Namibia, continue to operate, but currently account for only approximately 25% of mine production. Artisanal operations, primarily in the Great Lakes Region of Central Africa, West Africa, South America, and Asia, currently account for the remaining 75% (Burt 2016). The world Ta mine production for 2017 was estimated at 1300 tonnes of Ta content (Polyak 2018b).

Larger deposits currently considered for development in industrialized countries, especially those operated by companies listed on Canadian or Australian stock exchanges, require resource and reserve estimates completed in accordance with a regulatory code such as NI 43-101 or Joint Ore Reserves Committee (JORC). The development of such deposits requires pre-feasibility and feasibility studies, and any development is required to comply with applicable environmental regulations. All of this takes time and money; hence, short-term market volatility, typical of specialty metals, prevents most grass-roots discoveries from coming into production in a single attempt. The prospects which were partially developed during the historic Ta price spikes of 1980, 1988, and 2000 (Fig. 9; and Simandl 2002) have existing infrastructure and established resources or reserves, and these have the best chance to be put in production during future Ta price increases. Nevertheless, there are considerable known resources delineated (Linnen et al. 2014; Mackay and Simandl 2014a) that could be brought into production if longer-term market forces were to render them commercially viable.

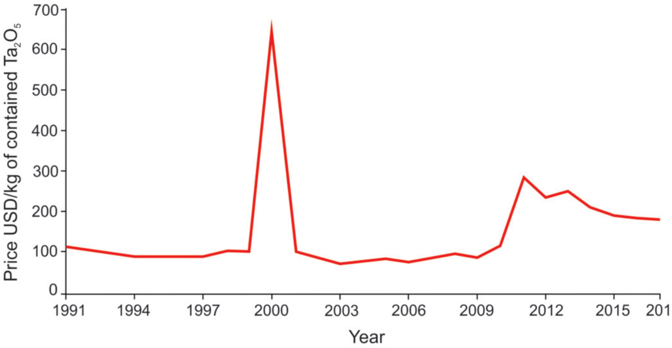

Figure 9. Price of tantalite reported as US dollars per kilogram of Ta_2O_5 content for the time period from 1991 to 2018. Updated from Mackay and Simandl (2014a) based on information contained in US Geological Survey commodity summaries. Prices are adjusted for inflation to 2012 US dollars.

Artisanal operations typically exploit soft, weathered crusts overlying pegmatites or related alluvial deposits, and in most cases mining and processing is by hand or uses primitive equipment. Processing of such ores is simple, generally consisting of little more than ground sluicing, such as at Nyabitare in Rwanda (Fig. 10), with further concentration in more central facilities. Consequently, artisanal operations require little or no infrastructure and can be rapidly wound down or reactivated in response to market conditions.

Notwithstanding these inherent advantages, artisanal Ta production has to be regarded as a supply risk. Artisanal miners do not develop mineral reserve or even resource estimates. They follow mineralization until it is exhausted and move on to the next deposit, if available. Furthermore, apart from the documented lax environmental and safety regulations in some of the countries, political and armed-conflict-related risks as well as child labour are also of concern. For decades, 'conflict minerals', including Ta, were sourced to a significant extent from conflict areas and proceeds of sales from these and other natural resources did provide some of the funding that helped to perpetuate ongoing conflicts between various fighting factions. However, over the last ten years, the situation has improved significantly due to public pressure and the efforts of end-users (high-technology industries), producers (mining and processing companies), and various governmental agencies in both Ta-producing and Ta-consuming countries. These important initiatives include the Dodd-Frank Act on conflict minerals and artisanal mining issues (USA), which is overseen by US Department of State Foreign Service, and the Directorate General of European Commission's regulations on conflict minerals. Other contributions include the International Tin Supply Chain Initiative (iTSCi), the Responsible Minerals Initiative (formerly the Conflict-Free Sourcing Initiative), and the efforts of the Tantalum-Niobium International Study Center. A concrete product of these efforts is a list of 40 'conflict-free' Ta smelters established by the Responsible Minerals Ini-

Figure 10. Ground sluicing at Nyabitare beryl–Sn–Ta–Nb-bearing weathered pegmatite, producing high grade tantalum-tin concentrate (western Rwanda). Ground sluicing is a simple technique of primary concentration, favoured by artisanal miners, as no power is required.

tiative (http://www.responsiblemineralsinitiative.org). However, further measures may be needed to completely eradicate conflict minerals from the Ta supply chain (Pickles 2017).

LONG-TERM AVAILABILITY OF Ta AND Nb

Reserves and Resources

From the geologist's point of view, Ta and Nb resources are plentiful. Global Ta 'reserves' were estimated by the United States Geological Survey (USGS) at more than 100,000 tonnes of contained Ta, and most of these 'reserves' are located in Australia (69,000 tonnes of Ta content) and Brazil (36,000 tonnes of Ta content) (Papp 2017b). However, according to the same source, JORC reserves for Australia are only 29,000 tonnes of Ta content. Such apparent discrepancies are due to a wide variety of factors listed and explained in Appendix C of the USGS commodity summaries (USGS 2017). For example, USGS sources include academic articles, company reports, PowerPoint presentations, trade journal articles, etc. Only small portions of these 'resource' and 'reserve' data are likely to be prepared in accordance with NI 43-101 or JORC procedures.

Burt (2009) and the Tantalum-Niobium International Study Center (www.tanb.org), using an extensive but confidential database incorporating most of the world's known deposits, estimated that the 'most likely resource base' (not NI-43-101 or JORC) for contained tantalum exceeded 300,000 tonnes, with Brazil and Australia being the two major sources. Put into perspective, this is over a century of world's Ta needs at the current rate of consumption.

Global Nb 'reserves' were estimated by the USGS at 4.3 million tonnes of contained Nb (Papp 2017a), with most located in Brazil (4.1 million tonnes of contained Nb) and Canada (200,000 tonnes). These estimates are subject to the same uncertainties as the Ta estimates discussed above.

Publicly available information on individual Nb and Ta deposits was compiled by Mackay and Simandl (2014a). Niobium and Ta grade-tonnage diagrams presented in this study are based on that information with minor updates (Fig. 11a, b). Unfortunately, as is the case in former studies, many of the resource estimates were not done in accordance with NI 43-101 or JORC guidelines and some of the deposits such as Tanco (Canada) may be almost completely mined out. Furthermore, many small deposits (weathered crusts overlying pegmatites and placers) that currently supply approximately 75% of tantalite-columbite concentrate are not shown because the grade and tonnage data are unavailable. Nevertheless, these diagrams are extremely useful for comparing the relative importance of the main Nb and Ta deposit types. They show that Nb- and Ta-containing deposits vary widely in terms of grade and tonnage (note that the spacing between isotonnage lines is logarithmic). The highest Nb_2O_5 grades and tonnages correspond to weathering-enriched carbonatite complex-related deposits (e.g. Araxá, Catalão I and II and Seis Lagos, Brazil) followed by hard-rock carbonatite-related deposits (e.g. Aley and Niobec Mine, Canada). Peralkaline-granite-related deposits also represent significant tonnages of contained Nb_2O_5 (e.g. Lovozero, Russia and Nechalacho, Canada). The highest Ta_2O_5 grades shown in Figure 11b correspond to pegmatites (e.g. Tanco, Canada; Morrua, Mozambique; and Wodgina, Australia). A large proportion of Ta resources is contained in a few large, relatively low-grade undeveloped peralkaline intrusion-hosted deposits (e.g. Ghurayyah, Saudi Arabia; Nechalacho, Canada).

Regardless of the accuracy of the above estimates, a global lack of ore will not be a key factor in any future supply disruption, as long as market forces can absorb the likely (if not inevitable) long-term reduction in tantalum ore grades and probable subsequent increased costs of production.

Additional Factors Relevant to Long Term Availability of Ta and Nb

Numerous small Ta-bearing pegmatites form clusters in northeastern Brazil, Colombia, Bolivia, Namibia, southern Russia, south-east Asia, India, USA, and Canada (Burt 2016). More than 280 Nb- and 160 Ta-bearing occurrences (Figs. 12 and 13) are known in Canada alone (Simandl et al. 2012), some of which have been worked on a small scale. However, under current market conditions, most of these deposits are not large enough to warrant development on their own. Packaging several nearby pegmatites together could improve the potential for their development. Using an inexpensive semi-mobile primary plant that could be moved from site to site, with a central upgrading plant for cleaning the rough concentrates, could make these individually sub-economic deposits collectively viable.

Another significant driver that could swing the pendulum back toward mechanized mining of Ta is the persistently pos-

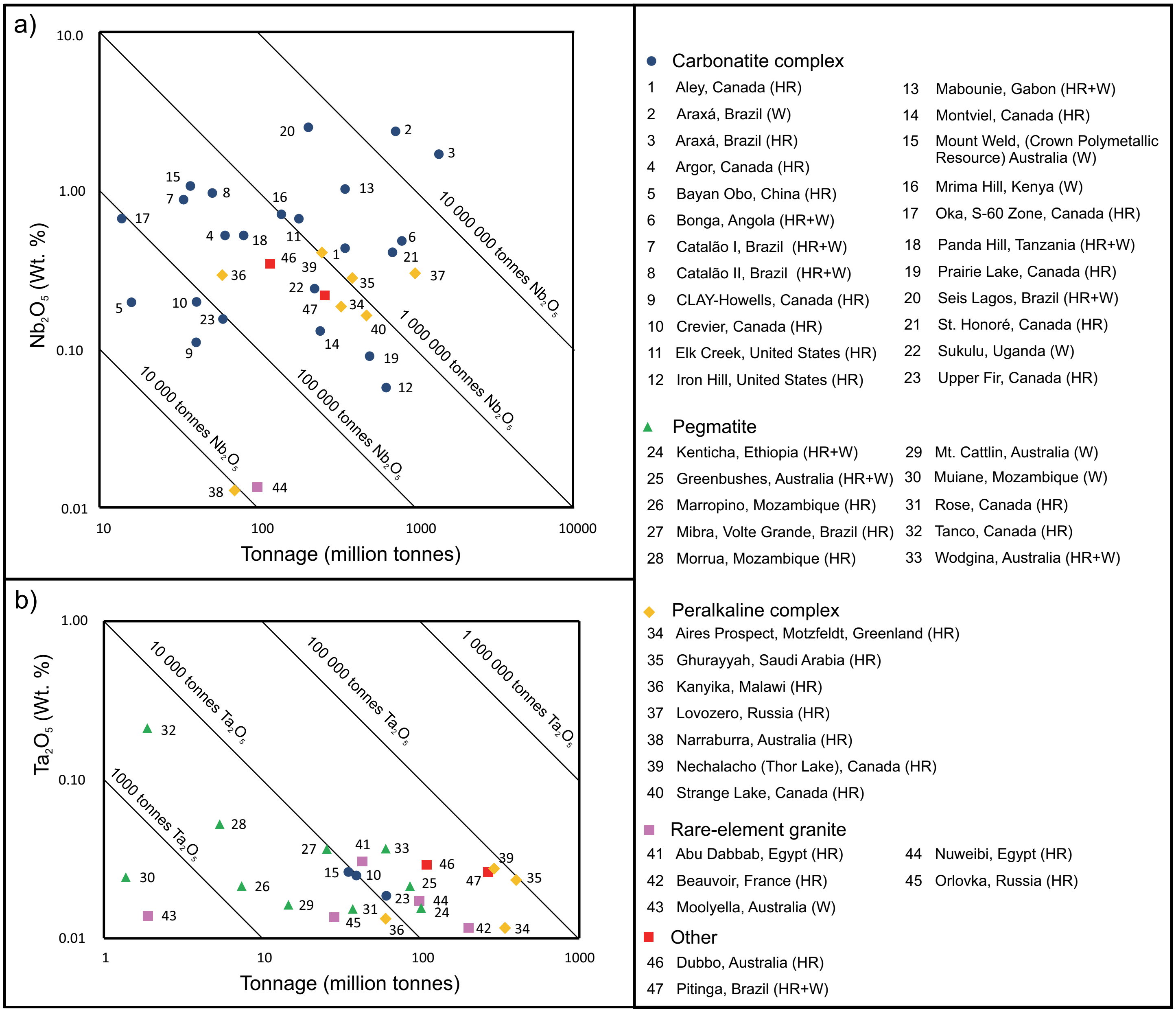

Figure 11. Grade and tonnage of a) Nb, and b) Ta deposits associated with carbonatite complexes relative to pegmatites, peralkaline complexes, and rare-element granites. Diagonal lines indicate isotonnage of contained metal oxides. Two deposits plotting along the same isotonnage line will have varying ore grades and tonnages, but will contain the same mass of Nb_2O_5 or Ta_2O_5. The highest Ta_2O_5 grades correspond to pegmatites. Peralkaline intrusive complexes have the largest resource in terms of contained tonnes of Ta_2O_5. The highest Nb_2O_5 grades and ore tonnages correspond to weathering-enriched carbonatite-complex-related deposits followed by hard-rock carbonatite-related deposits. Peralkaline-complex-related deposits also represent significant ore tonnages and tonnages of contained Nb_2O_5. Relevant references to grade and tonnage sources of information are available in Mackay and Simandl (2014a); with updates from Arrowhead Resources Ltd. projects, Vallieres et al. (2013), Anglo American PLC (2015), and Pittuck et al. (2015) provided in this paper. Abbreviations: (HR) hard-rock ore, (W) weathered ore, (HR+W) hard-rock and weathered ore combined. Modified from Mackay and Simandl (2014a).

itive market fundamentals for lithium raw materials, and the increasing use of Li in batteries (Gruber et al. 2011; Wanger 2011; Perks 2017; Jaskula 2017). Tantalum-bearing zones in pegmatites commonly occur adjacent to and within the same zone as Li mineralization and Ta was historically a co-product of several significant lithium mineral producers, such as Greenbushes in Western Australia and Bikita in Zimbabwe. The increasing demand for Li is a potential catalyst for resurrecting historic Ta producers and developing new mines in which Ta and Li could be recovered from the same pegmatite body, such as the Wodgina pegmatite, and Mount Marion and Mount Cattlin pegmatites in Western Australia (Tamlin 2017). The Pilgangoora Ta–Li project, Western Australia (Pilbara Minerals Limited), the Mibra Ta mine in Brazil (AMG Company), the Pakeagama project, Ontario, Canada (Tamlin 2017), the Rose Ta–Li project in Québec, Canada (Lavallée 2017), and

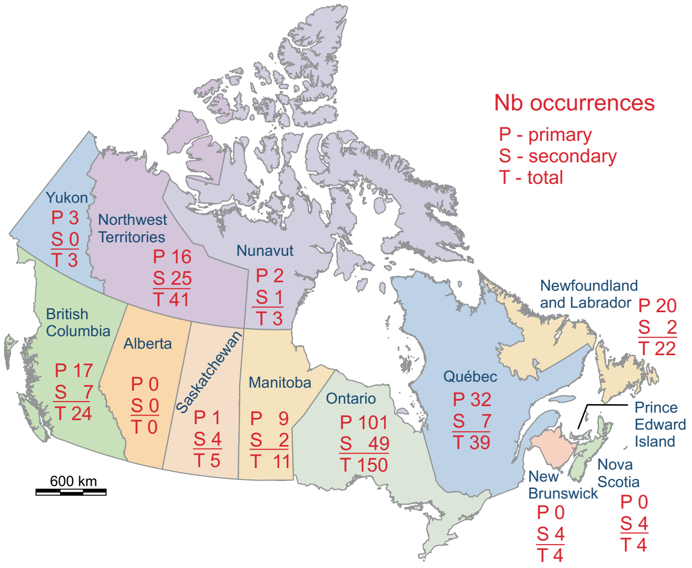

Figure 12. Distribution of Nb-bearing occurrences in Canada (Simandl et al. 2012). The term 'primary' identifies occurrences where Nb is the main substance of economic interest. The term 'secondary' refers to occurrences where Nb is listed as potential co-product. The terms carry no implications as to the origin of mineralization.

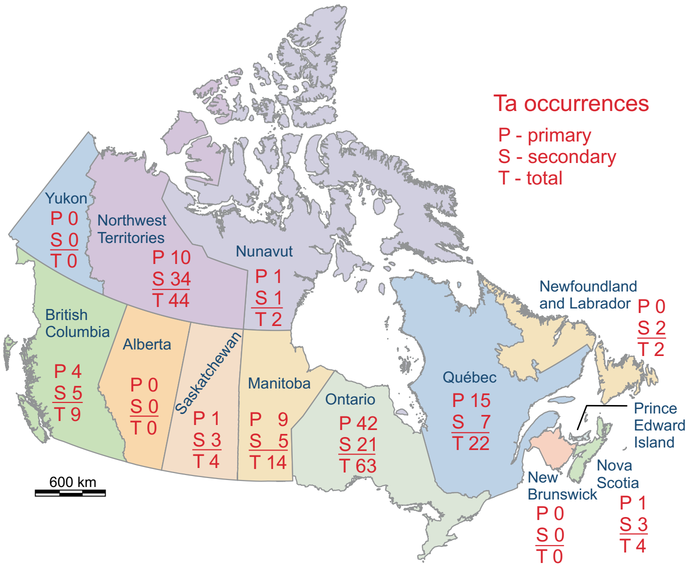

Figure 13. Distribution of Ta-bearing occurrences in Canada (Simandl et al. 2012). The term 'primary' identifies occurrences where Ta is the main substance of economic interest. The term 'secondary' refers to occurrences where Ta is listed as potential co-product. The terms carry no implications as to the origin of mineralization.

the Separation Rapids pegmatite in Ontario, Canada (Avalon Advanced Materials Inc.), are all examples of potential Ta–Li co-producers.

Historically, the feasibility of Ta extraction from Sn slags was strongly influenced by market conditions (Roethe 1989) and this is still happening today. Only Ta-rich slags can be processed if Ta_2O_5 prices are low; however, currently sub-economic Sn slag stockpiles that contain Ta may provide a buffer should Ta shortages materialize.

In the long term, potential REE extraction from large, peralkaline-intrusion-related deposits may yield Nb and Ta as by-products of REE extraction. Examples include deposits such as Nechalacho and Strange Lake in Canada (Ciuculescu et al. 2013; Gowans et al. 2017) and the Motzfeldt Sø (Ta–Nb–REE–Zr–U) deposit in Greenland (Tukiainen 1988). However, in most of these cases, unconventional or currently commercially unproven processing technology is required. Furthermore, as in the case of carbonatite-related deposits, the $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$ ratios of concentrates from such deposits will determine their Ta potential.

New Exploration Methods and Other Developments

It is expected that new deposits will be discovered as exploration methods for Nb and Ta are optimized. Some recent and significant breakthroughs include customizing and optimizing the use of portable X-Ray Fluorescence to provide sufficiently accurate and precise chemical analyses for specialty metals directly in the field (Simandl et al. 2014), optimization of indicator mineral-based exploration methodology to detect Nb–Ta mineralization (e.g. Mackay and Simandl 2015; Mackay et al. 2016), and the use of exploration biogeochemistry (Fajber et al. 2015). Test sites used to improve these methods were located in the Canadian Cordillera and included the Aley carbonatite (83.8 million tonnes of proven and probable reserve at 0.50% Nb_2O_5; Jones et al. 2014) and the Upper Fir carbonatite (indicated resources of 48.4 million tonnes grading 197 ppm Ta_2O_5 and 1,610 ppm Nb_2O_5 and inferred resources of 5.4 million tonnes grading 191 ppm Ta_2O_5 and 1,760 ppm Nb_2O_5; Kulla and Hardy 2015). The Aley deposit was detectable using indicator minerals in stream sediments more than 11 km downstream from the deposit (Mackay and Simandl 2014b; Mackay et al. 2016). The Upper Fir carbonatite was used to test a biogeochemical exploration approach. The results suggest that twigs and needles of fir and spruce are acceptable sampling media and that La, Ce, Pr, Nd, Sm, Dy, Fe, Nb, Ta, P, and Y are promising pathfinder elements. Ashing of twigs concentrated all pathfinders above the lower limit of detection of a commercial analytical procedure involving HNO_3 digestion followed by ICP-MS/ICP-AES analysis (Fajber et al. 2015). A comprehensive review of modern geophysical techniques (with emphasis on gravity, magnetic, and radiometric methods) used in exploration for intrusion-related rare metal deposits, including those containing Ta and Nb, is provided by Thomas et al. (2016). This review demonstrates the utility of such methods in delineating intrusions hosting rare metals, in modelling their third dimension, and in helping to better focus on mineralization. This is achieved using predominantly Canadian examples such as the Oka carbonatite complex, the Tanco pegmatite, and the Nechalacho and Strange Lake peralkaline intrusions.

Current and future effects of recycling in the Ta supply chain are hard to quantify due to ongoing shifts in uses of Ta. Overall, the recycling of Ta scrap generated during the manufacturing process has increased since the 1970's (Nassar 2017). According to the same study, the overall end-of-life recycling rate of Ta declined from the 22–25% range in the 1990's to

18% today. This decline coincides with the shift in use of Ta from carbides to sputtering targets, chemicals, and capacitors. The latter are not being recycled at their end-of-life in significant quantities (Nassar 2017). Furthermore, the potential for recovering Ta from end-of-life electronics varies from product to product (Ueberschaar et al. 2017).

SUMMARY AND CONCLUSIONS

Carbonatite-related deposits supplying concentrates dominated by pyrochlore are currently the main source of Nb in the form of ferroniobium. Deposits related to pegmatites of the rare-element class, belonging to the LCT (lithium–cesium–tantalum) family, are the main sources of primary Ta concentrates, which consist predominantly of columbite–tantalite group minerals. The situation is unlikely to change within the next 5 to 10 years.

The mineralogy of the ore is extremely important in ranking of projects according to their development potential. It controls at least in part the $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$ ratio of the concentrate, and indirectly constrains processing options. The higher the $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$ ratio is, the better the chance that Ta_2O_5 can be economically recovered.

Major Nb-producing mines are mechanized with relatively well-established resources and reserves. Approximately 90% of Nb (in the form of ferroniobium) currently originates from Brazil, with the majority of that coming from just one mine; therefore, Nb is classified as a ‘critical metal’.

Most of the primary Ta raw materials are currently derived from the historically politically unstable Great Lakes Region of Central Africa, largely from artisanal mines without resource estimates prepared under a certification system. These are the main reasons why Ta is considered to be a critical material, with a significant risk of supply disruption.

Tantalum coexists with Li in several pegmatite deposits in Australia, North America, and South America. The demand for Li minerals is growing rapidly, triggering efforts for reactivating several historic mines and developing new mechanized mines with known Li and Ta resources. If these efforts are successful, the risk of future Ta supply disruptions could be significantly reduced. It is too early to predict to what extent this trend towards Li–Ta coproduction will affect the current Ta supply chain.

Significant Nb and Ta resources are also identified within several known peralkaline-intrusion-related REE deposits; however, in the short- and medium-term, these resources are unlikely to be developed and significantly impact Ta and Nb markets.

From a technical-economic standpoint, the risk of future shortages of Nb and Ta raw materials is minimal, despite their designation as critical minerals. Market elasticity is expected to absorb the long-term reduction in ore grades and depletion of Ta and Nb resources in weathered crusts by allowing for corresponding increased costs of production. Continued improvement of exploration methods targeting Ta and Nb deposits, in combination with possible recovery of Ta and Nb as co-products of REE, Sn, and Li, will reduce this risk even further.

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REFERENCES

Anglo American PLC, 2015, Annual Report 2014: Anglo American PLC, London, UK, http://www.angloamerican.com/~/media/Files/A/Anglo-American-PLC-V2/report-builder-2014/annual-report/aa-ar14-interactive-final.pdf, accessed April 21, 2017.

Atencio, D., Andrade, M.B., Christy, A.G., Gieré, R., and Kartashov, P.M., 2010, The pyrochlore supergroup of minerals: Nomenclature: The Canadian Mineralogist, v. 48, p. 673–698, https://doi.org/10.3749/canmin.48.3.673.

Burt, R.O., 2009, Tantalum – a rare metal in Abundance?: Tantalum-Niobium International Study Center, TIC Bulletin No.141 p. 2–5, https://www.tanb.org/images/Bulletin_141_final.pdf, accessed September 13, 2017.

Burt, R.O., 2016, Much ado about Tantalum. Again: https://tanb.org/images/Much%20ado%20about%20tantalum(1).pdf, accessed August 22, 2017.

Černý, P., and Ercit, T.S., 1985, Some recent advances in the mineralogy and geochemistry of Nb and Ta in rare-element granitic pegmatites: Bulletin de Minéralogie, v. 108, p. 499–532.

Černý, P., and Ercit, T.S., 2005, The classification of granitic pegmatites revisited: Canadian Mineralogist, v. 43, p. 2005–2026, https://doi.org/10.2113/gscanmin.43.6.2005.

Černý, P., Ercit T.S, and Wise, M.A., 1992, The tantalite-tapiolite gap: natural assemblages versus experimental data: Canadian Mineralogist, v. 30, p. 587–596.

Černý, P., London, D., and Novák, M., 2012, Granitic pegmatites as reflections of their sources: Elements, v. 8, p. 289–294, https://doi.org/10.2113/gselements.8.4.289.

Chudy, C.T., 2014, The petrogenesis of the Ta-bearing Fir carbonatite system, east central British Columbia, Canada: Unpublished Ph.D. thesis, University of Victoria, 553 p.

Ciuculescu, T., Foo, B., Gowans, R., Hawton, K., Jacobs, C., and Spooner, J., 2013, Technical report disclosing the results of the feasibility study on the Nechalacho rare earth elements project: Avalon Rare Metals Inc., Toronto, Ontario, Canada, 307 p., http://avalonadvancedmaterials.com/_resources/projects/may_2013_ni43_report.pdf, accessed August 25, 2017.

European Commission, 2017, Study on the review of the list of Critical Raw Materials- Final Report, European Commission, 92 p., https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en, accessed May 12, 2018.

Fajber, R., Simandl, G.J., and Luck, P., 2015, Exploration for carbonatite-hosted niobium-tantalum deposits using biogeochemical methods (orientation survey), Blue River Area, British Columbia, Canada, *in* Lasemi, Z., *ed*., Proceedings of the 47th Forum on the Geology of Industrial Minerals: Illinois State Geological Survey, Circular 587, 18 p., https://www.isgs.illinois.edu/sites/isgs/files/files/publications/47th-Forum-Fajber.pdf, accessed May 12, 2018.

Gowans, R.M., Lewis, W.J., and Zalnieriunas, R.V., 2017, NI 43-101 technical report for the updated mineral resource estimate for the Strange Lake property, Québec, Canada, 144 p., https://www.questrareminerals.com/pdfs/Strange-Lake-Updated-TR-2017-Final.pdf , accessed September 10, 2017.

Groulier, P-A., Ohnenstetter, D., Andre-Mayer, A-S., Zeh, A., Solgadi, F., Moukhsil, A., and El Basbas, A., 2014, Étude des minéralisations en Nb-Ta de l'intrusion alcaline de Crevier: Energie et Ressources Naturelles du Québec, MB 2014-33, 68 p.

Gruber, P.W., Medina, P.A., Keoleian, G.A., Kesler, S.E., Everson, M.P. and Wallington, T.J., 2011, Global Lithium availability: A constraint for electric vehicles?: Journal of Industrial Ecology, v. 15, p. 760–775, https://doi.org/10.1111/j.1530-9290.2011.00359.x.

Hogarth, D.D., 1989, Pyrochlore, apatite and amphibole: Distinctive minerals in carbonatites, *in* Bell, K. *ed.,* Carbonatites, Genesis and Evolution, Unwin Hyman, London; p. 105–148.

Hogarth, D.D., Williams, C.T., and Jones, P., 2000, Primary zoning in pyrochlore group minerals from carbonatites: Mineralogical Magazine, v. 64, p. 683–697, https://doi.org/10.1180/002646100549544.

Jones, S., Merriam, K., Yealland, J., Rotzinger, R., and Simpson, R.G., 2014, Technical Report on mineral reserves at the Aley project, British Columbia, Canada:

Taseko Mines Limited, 291 p.

Kulla, G., and Hardy, J., 2015, NI 43-101 Blue River Tantalum–Niobium Project British Columbia, Canada - Project Update Report, Commerce Resources Corp., 138 p., https://www.commerceresources.com/assets/179115_Blue_River_Technical_Report_March_2015_FINAL.pdf, accessed August 22, 2017.

Jaskula, B.W., 2017, Lithium: Mineral Commodity Summaries 2017: U.S. Geological Survey, p. 100–101, https://doi.org/10.3133/70180197.

Lavallée, J.S., 2017, Critical Elements submits an environmental impact study for its Rose lithium-tantalum project, Critical Elements Corporation: https://www.cecorp.ca/en/critical-elements-submits-environmental-impact-study-rose-lithium-tantalum-project/, accessed August 21, 2017.

Le Maitre, R.W., *editor,* 2002, Igneous Rocks: A Classification and Glossary of Terms: Cambridge, Cambridge University Press, 236 p., https://doi.org/10.1017/CBO9780511535581.

Linnen, R.L., Trueman, D.L., and Burt, R.O., 2014, Tantalum and niobium, *in* Gunn, G., *ed.*, Critical Minerals Handbook, J. Wiley and Sons, p. 361–384, https://doi.org/10.1002/9781118755341.ch15.

London, D., 2008, Pegmatites: Canadian Mineralogist, Special Publication, v. 10, 347 p.

London, D., 2014, A petrologic assessment of internal zonation in granitic pegmatites: Lithos, v. 184–187, p. 74–104, https://doi.org/10.1016/j.lithos.2013.10.025.

Mackay, D.A.R., and Simandl, G.J., 2014a, Geology, market and supply chain of niobium and tantalum — a review: Mineralium Deposita, v. 49, p. 1025–1047, https://doi.org/10.1007/s00126-014-0551-2.

Mackay, D.A.R., and Simandl, G.J., 2014b, Portable X-ray fluorescence to optimize stream sediment chemistry and indicator mineral surveys, case 1: Carbonatite-hosted Nb deposits, Aley carbonatite, British Columbia, Canada, *in* Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines: British Columbia Geological Survey Paper 2014-1, p. 183–194.

Mackay, D.A.R., and Simandl, G.J., 2015, Pyrochlore and columbite-tantalite as indicator minerals for specialty metal deposits: Geochemistry: Exploration, Environment, Analysis, v. 15, p. 167–178, https://doi.org/10.1144/geochem2014-289.

Mackay, D.A.R., Simandl, G.J., Ma, W., Redfearn, M., and Gravel, J., 2016, Indicator mineral-based exploration for carbonatites and related specialty metal deposits — A QEMSCAN® orientation survey, British Columbia, Canada: Journal of Geochemical Exploration, v. 165, p. 159–173, https://doi.org/10.1016/j.gexplo.2016.03.005.

Melcher, F., Graupner, T., Gäbler, H.-E., Sitnikova, M., Henjes-Kunst, F., Oberthür, T., Gerdes, A., and Dewaele, S., 2015, Tantalum–(niobium–tin) mineralisation in African pegmatites, and rare metal granites: Constraints from Ta–Nb oxide mineralogy, geochemistry and U–Pb geochronology: Ore Geology Reviews, v. 64, p. 667–719, https://doi.org/10.1016/j.oregeorev.2013.09.003.

Melcher, F., Graupner, T., Gäbler, H-E., Sitnikova, M., Oberthür, T., Gerdes, A., Badanina, E., and Chudy, T., 2017, Mineralogical and chemical evolution of tantalum–(niobium–tin) mineralisation in pegmatites and granites. Part 2: Worldwide examples (excluding Africa) and an overview of global metallogenetic patterns: Ore Geology Reviews, v.89, p. 946–987, http://dx.doi.org/10.1016/j.oregeorev.2016.03.014.

Nassar, N.T., 2017, Shifts and trends in the global anthropogenic stocks and flow of tantalum: Resources, Conservation and Recycling, v. 125, p. 233–250, https://doi.org/10.1016/j.resconrec.2017.06.002.

Neuendorf, K.K.E., Mehl, J.P., and Jackson, J.A., 2005, Glossary of geology (5th edition): American Geological Institute, Alexandria, USA, 779 p.

Papp, J.F., 2017a, Niobium (columbium): Mineral Commodity Summaries 2017: U.S. Geological Survey, p. 116–117, https://doi.org/10.3133/70180197.

Papp, J.F., 2017b, Tantalum: Mineral Commodity Summaries 2017, U.S. Geological Survey, p. 166–167, https://doi.org/10.3133/70180197.

Papp, J.F., 2017c, Niobium (advance release): 2015 Minerals Yearbook: U.S. Geological Survey, p. 52.0–52.7.

Perks, C., 2017, Australia the land of lithium: Industrial Minerals, No. 593, p. 24–27.

Pickles, S., 2017, Tantalum supply chains today: how responsible are they?: Tantalum–Niobium International Study Center, Bulletin, No. 170, p.23–26.

Pittuck, M.F., Parsons, B., and Bair, D., 2015, NI 43-101 technical report updated mineral resource estimate Elk Creek niobium project, Nebraska: NioCorp Developments Limited, 299 p., http://www.otcmarkets.com/financialReportViewer?symbol=NIOBF&id=148620, accessed June22, 2018.

Polyak, D.E., 2018a, Niobium: Mineral Commodity Summaries 2018: U.S. Geological Survey, p. 114–115, https://doi.org/10.3133/70194932.

Polyak, D.E., 2018b, Tantalum: Mineral Commodity Summaries 2018: U.S. Geological Survey, p. 164–165, https://doi.org/10.3133/70194932.

Roethe, G., 1989, Processing of tantalum and niobium ores, *in* Möller, P., Černý P., and Saupé, F., *eds.*, Lanthanides, Tantalum and Niobium: Society for Geology Applied to Mineral Deposits, Special Publication, v. 7, p. 331–341, https://doi.org/10.1007/978-3-642-87262-4_17.

Roskill Information Services, 2016, Superalloys: an introduction: Tantalum–Niobium International Study Center, Bulletin No. 167, p. 10–24, https://www.tanb.org/images/T_I_C_Bulletin_no_167_(October_2016).pdf , accessed September 12, 2017.

SGS Canada Inc – Geostat, 2010, Technical Report Niobium and Tantalum resource estimation update of the Crevier deposit North of Lac St-Jean, Quebec, Canada: Report submitted to Crevier Minerals Inc.: MDN Inc. & Crevier Minerals Inc., Blainville Quebec, 143 p., http://niobaymetals.com/wp/wp-content/uploads/2015/08/NI43101July29th2010finalmdn2.pdf, accessed August 5, 2017.

Simandl, G.J., 2002, Tantalum market and resources: An overview: Geological fieldwork 2001: British Columbia Ministry of Energy and Mines, Paper 2002-1, p. 313–318, http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Documents/2001/22-GS-p313-318.pdf, accessed August 5, 2017.

Simandl, G.J., 2014, Geology and market-dependent significance of rare earth element resources: Mineralium Deposita, v. 49, p. 889–904, https://doi.org/10.1007/s00126-014-0546-z.

Simandl, G.J, Jones, P.C, and Rotella, M., 2002, Blue River carbonatites, British Columbia- primary exploration targets for tantalum: Ministry of Energy, Mines and Petroleum Resources, Exploration and Mining in British Columbia 2001, p. 73–82, http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/ExplorationinBC/Documents/2001_09-GSimandl.pdf, accessed August 5, 2017.

Simandl, G.J., Prussin, E.A., and Brown, N., 2012, Specialty Metals in Canada: British Columbia Ministry of Energy and Mines, British Columbia Geological Survey, Open File 2012-07, 48 p., http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/2012/Pages/2012-7.aspx, accessed August 29, 2017.

Simandl, G. J., Paradis, S., Stone, R.S., Fajber, R., Kressall, R.D., Grattan, K., Crozier, J., and Simandl, L.J., 2014, Applicability of handheld X-ray fluorescence spectrometry in the exploration and development of carbonatite-related niobium deposits: a case study of the Aley Carbonatite, British Columbia, Canada: Geochemistry: Exploration, Environment, Analysis, v. 14, p. 211–221, https://doi.org/10.1144/geochem2012-177.

Simandl, G.J., Akam, C., and Paradis, S., 2015, Which materials are 'critical' and 'strategic', *in* Simandl, G.J., and Neetz, M., *eds.*, Symposium on Strategic and Critical Materials Proceedings, November 13–14, 2015, Victoria, British Columbia: British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-3, p. 1–4, http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Papers/Documents/P2015-3/01%20Simandl.pdf, accessed August 25, 2017.

Simmons, Wm.B.S., and Webber, K.L., 2008, Pegmatite genesis: state of the art: European Journal of Mineralogy, v. 20, p. 421–438, https://doi.org/10.1127/0935-1221/2008/0020-1833.

Tamlin, M., 2017, Tantalum supply from the lithium industry: Tantalum–Niobium International Study Center, T.I.C. Bulletin No. 168, p. 14–22, https://www.tanb.org/images/T_I_C_Bulletin_no_168_(January_2017).pdf, accessed September 13, 2014.

Thomas, M.D., Ford, K.L., and Keating, P., 2016, Review paper: Exploration geophysics for intrusion-hosted rare metals: Geophysical Prospecting, v. 64, p. 1275–1304, https://doi.org/10.1111/1365-2478.12352.

Trueman, D.L, and Černý, P., 1982, Exploration for rare-element granitic pegmatites, *in* Černý, P., *ed.*, Granitic pegmatites in science and industry: Mineral Association of Canada Short Course, v. 8, Winnipeg, Canada, p. 463–493.

Tukiainen, T., 1988, Niobium-tantalum mineralisation in the Motzfeldt centre of the Igaliko Nepheline Syenite Complex, South Greenland, *in* Boissonnas, J., and Omenetto, P., *eds.*, Mineral Deposits within the European Community: Society for Geology Applied to Mineral Deposits, v. 6, p. 230–246, https://doi.org/10.1007/978-3-642-51858-4_13.

Ueberschaar, M., Jalalpoor, D.D., Korf, N., and Rotter, V.S., 2017, Potentials and barriers for tantalum recovery from waste electric and electronic equipment: Journal of Industrial Ecology, v. 21, p. 700–714, https://doi.org/10.1111/jiec.12577.

USGS. U.S. Geological Survey, 2017, Appendix C –Reserves and resources: Mineral Commodity Summaries 2017: U.S. Geological Survey, p. 195–198, https://doi.org/10.3133/70180197.

USGS. U.S. Geological Survey, 2018, Final List of Critical Minerals 2018: Executive Order 13817, Department of the Interior, https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018, accessed June 14, 2018.

Vallieres, D., Pelletier, P., Gaultier, P., Felatte, G., Tremblay, J.F., and Sirois, R., 2013, NI 43-101 technical report, Update on Niobec Expansion, December 2013: Report prepared for IAMGOLD Corporation.

Wanger, T.C., 2011, The Lithium future—resources, recycling, and the environment: Conservation Letters, v. 4, p. 202–206.

Woolley, A.R., and Kjarsgaard, A., 2008, Paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: evidence from a global database: The Canadian Mineralogist, v. 46, p. 741–752.

Zaitsev, V., and Kogarko, L., 2012, Sources and perspectives of REE in the Lovozero Massif (Kola Peninsula, Russia): Eur Mineral Conf 1: EMC2012–EMC2290, http://meetingorganizer.copernicus.org/EMC2012/EMC2012-290.pdf, accessed August 31, 2017.

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