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Resilience in the tantalum supply chain

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ABSTRACT

Tantalum, considered one of the critical elements by many countries, is a widely used metal in industries such as electronics, aerospace and automotive. The tantalum market has experienced several disruptions and subsequent price swings in the past, implying problems with its supply chain resilience and stability. In this study, we trace the entire value chain of the tantalum industry from mining to the intermediate and the downstream industries. Our interest is to see how dependent the tantalum supply chain is on specific countries and regions, how exposed primary production is to disruptions, and what mechanism counteracts disruption. This study assesses the tantalum supply chain from a resilience perspective rather than an investigation of any specific disruption in the system. We analyze several resilience-promoting mechanisms such as: (a) diversity of supply, (b) material substitution, (c) recycling and (d) stockpiling. We evaluate each of these mechanisms, and find that even though diversity of supply and stockpiling mechanisms have been decreasing for years, the tantalum supply chain has been flexible in its response to disruption. We find a much larger supply from unaccounted artisanal and small mining sources than expected based on official statistics, and estimate the unaccounted production in Africa, which shows an almost 250 percent increase from around 600 tons in 2004 to more than 2000 tons in 2014.. Besides flexible primary production from small-scale mining, we identfy rapid material substitution and increasing availability of waste and scrap as the main reasons behind the observed supply chain resilience.

1. Introduction

Tantalum, considered a critical element by many industrialized countries, is a widely used metal in industries such as electronics, aerospace, and automotive. The metal was discovered in 1802, a year after the discovery of niobium (Nb). Both metals share similar chemical properties and the ore is commonly referred either as columbite or tantalite (TIC, 2016a). Relative to any of the “major” metals such as copper, iron, or nickel, its annual production is minute. However, because it is produced in countries like The Democratic Republic of the Congo (DRC) and other parts of Africa where mining has financed rebel movements, tantalum is classified as a conflict mineral (Nest, 2011), along with tin (Sn), gold (Au) and tungsten (W).

Our interest is to see how dependent the tantalum supply chain is on specific countries and regions, how exposed primary production is to disruptions, and what mechanism counteract disruption. This study assesses the tantalum supply chain from a resilience perspective rather than an investigation of any specific disruption in the system. We aimed to analyze several resilience-promoting mechanisms such as: (a) diversity of supply, (b) material substitution, (c) recycling and (d) stockpiling.

In the past decades, the tantalum market has experienced disruptions and significant price swings, which imply problems with its supply chain resilience and stability. The metal therefore makes an interesting case study on the resilience of metals supply chains, especially in light of a previous study on the resilience of the supply chain of rare earth elements (REEs) that focused on neodymium magnets (Sprecher et al., 2015, 2017). One of the main findings of that study was that disruptions caused by export constraints put in place by the main producer of REEs (China) gave rise to significant illegal mining and exports that eventually contributed up to 40 percent of total world production. The authors speculated that the relatively novel phenomenon of illegal mining and smuggling actually helped increase the resilience of the REEs supply chain (since it allowed for an alternative method of obtaining raw materials when official production was constrained). However, because of its inherently opaque nature, they believed it

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would, in all likelihood, have detrimental effects on long term supply chain resilience.

Illegal mining and smuggling have been an unfortunate fixture of the tantalum supply chain for decades. Recently, Deetman et al. (2017) employed substance flow analysis (SFA) to estimate the European consumption of tantalum and found that the total quantity of tantalum consumed by Europe alone in a single year is higher than the reported global production of tantalum. Furthermore, and confirming earlier findings of Bleischwitz et al. (2012), global consumption of tantalum and tantalum-containing products do not match the production statistics of either the USGS (US Geological Survey) or the TIC (Tantalum-Niobium International Study Center). It seems likely that these agencies count only primary mine production and government authorized artisanal and small-scale mining (ASM). Thus, the data neglect the large quantity of tantalum from unauthorized, semi-illegal mining operations in Africa and associated illegal trade that feeds into the global market.

ASM extraction from soft alluvial deposits and semi-pegmatite ores is easy to mine and does not require significant capital investment. Informal sources have profound effects on tantalum prices and the sustainability of the industry, affecting the operations of established large scale mining (LSM) companies in Australia, Canada, Brazil, and elsewhere. ASM production at hundreds of sites also responds rapidly to price fluctuations compared to LSM mining, which require significant capitalization and years to start-up.

The popularity of resilience as a scientific framework stems from its application in ecology, where it is used to analyze the ability of a natural ecosystem to either resist or recover from disruptions (Holling, 1996). This ecology-based definition of resilience forms the basis of resilience work in the fields of information and communication sciences (Laprie, 2008) and manufacturing supply chain resilience (Zhang and Van Luttervelt, 2011). As reviewed by Wang et al. (2016), most of the studies dealing with supply chain resilience have concentrated on the abrupt disruptions in the supply chains of firms or products. These types of studies address financial or commercial risks arising from poor quality or sub-optimal supply chains and follow a qualitative methodology, or use a quantitative simulation-based framework that incorporates concepts of resilience into the process of supply chain design (Craighead et al., 2007; Huang et al., 2007; Sheffi and Rice, 2005; Christopher and Peck, 2004). Many of these studies deal with resilience either from a perspective of mitigation or response measures.

The concept of a resilient supply chain has also been integrated with the traditionally used concept of risk assessment of the supply chain of individual firms (Peck, 2003). Studies assessing the criticality of minerals have often used supply risk as a quantifiable concept (European Commission, 2014; US DoE, 2011). Previous academic work has assessed supply risk of various minerals from different angles: geological availability (Machacek and Kalvig, 2016), geo-political availability (Mancheri et al., 2013; Habib et al., 2016), economic importance (Mancheri, 2015; Mancheri, 2012; Graedel et al., 2015) and sustainability (Bailey et al., 2017). A common criticism of these concepts is that they are static in nature. This makes sense for geological availability, but less so for societal indicators such as geo-political availability and economic importance. In a review of material criticality studies, Dewulf et al. (2016) suggested that resilience become a core component of future material criticality analyses, precisely because resilience inherently takes a dynamic (i.e., time-dependent) approach.

Tantalum is mined both as a primary product and as a byproduct from tin, niobium, and lithium extraction. Of the more than 70 identified tantalum-containing minerals, tantalite $(Fe,Mn)(Ta,Nb)_2O_6]$, microlite $[(Na,Ca)Ta_2O_6\ (O,OH,F)]$, and wodginite $[(Ta,Nb,Sn,Mn,Fe)O_2]$ are of greatest economic significance (USGS, 2014a). Tantalum ore is composed of both tantalum and non-tantalum containing minerals, and the Ta_2O_5-equivalent content is typically 0.02–0.04 percent. Low-grade tantalum ore is physically concentrated (beneficiation) to a concentrate of 20–40 percent Ta_2O_5-equivalent at the mining site before sale to smelters (Linnen et al., 2014). Tantalum minerals are priced according to Ta_2O_5-equivalent content.

Even though production of tantalum is minute compared to base metals, its reserves are not. Reserves are defined as the resources that could be economically extracted or produced. However, the term 'reserves' does not necessarily signify that extraction facilities are in place and extraction is economically viable (King, 2011).. The tantalum content of each deposit is essential in estimating the deposit's profitability. According to USGS estimates, Brazil and Australia have the largest reserves, holding more than 85 percent of the global reserves and other reserves are in Canada and African nations. Estimates of the most likely resource base by the TIC show that about 40 percent is situated in South America and about 21 percent in Australia. Tantalum is also produced in Brazil, Malaysia, and Thailand from "tin slag," a by-product of tin smelting. Tantalum raw materials are also being explored in Canada, Colombia, Egypt, Madagascar, Namibia, Saudi Arabia, Sierra Leone, South Africa, Tanzania, Venezuela, and Zimbabwe. Estimated global reserves of tantalum are large and more than sufficient to meet global demand for the foreseeable future, possibly the next 500 years. Therefore, geological availability does not appear to be a major concern for the supply of tantalum.

As of 2017, there are only a handful of countries producing tantalum ore but there are very large differences in production quantities among these countries. Australia used to be the largest producer, but its share declined drastically after the main producing mine closed in 2008. Brazil is a major primary mine producer while large quantities are produced in the DRC, Rwanda, and other African countries by artisanal miners. Additional quantities are produced intermittently or at low levels in Australia, Burundi, Malaysia, Mozambique, Namibia, Nigeria, Thailand, and Zimbabwe (USGS, 2016).

ASM operations greatly contribute to the opaque and even secretive nature of the tantalum industry. Although recent legislation and guidelines have pushed buyers to ensure purchased mineral is conflict free, it appears a large share of unaccounted supply still emerges from Central African countries. The quantity of production does not match either the tantalum contained in intermediate and final products, nor does it correspond to the resource base and global reserves, as most of these proven resources are concentrated in well-developed markets rather than in African countries (Fig. 1). There have been attempts – both governmental and non-governmental – to prevent trade in conflict minerals including tantalum (Young, 2015; Bleischwitz et al., 2012). One such major initiative is section 1502 of the Dodd-Frank Act, which essentially requires US companies to report to the US Securities and Exchange Commission (SEC) and disclose whether the tantalum or other conflict minerals they buy originate in a conflict region (SEC, 2011). A similar law was introduced in the EU parliament in June 2016 (EU Parliament, 2016) and expected to be implemented by 2021.

Tantalum concentrate is mainly processed by smelters in industrialized countries such as China, Japan, Germany, and the USA. Ta_2O_5 concentrate is dissolved in acid at high temperatures to extract K-salt (potassium fluortantalate, potassium fluorotantalate, potassium heptafluorotantalate, or potassium tantalum fluoride) or purified into Ta_2O_5 (tantalum pentoxide or tantalum oxide). Further processing results in tantalum metal powder and other tantalum-containing materials (TIC, 2016a).

Fig. 2 shows the number of major processing companies in different countries. China tops the list with 16 smelting companies. These numbers may not be completely accurate as during our investigation we found a number of small scale companies who process tantalum in China, Korea, Kazakhstan, and the US and they are not listed in the figure. A study by Achebe identified a total of 48 smelting and refining facilities worldwide, with China hosting 19, the US and Mexico 11 facilities each, Europe having 8 facilities, and Eurasia, including Japan, India, Thailand, Kazakhstan, and Russia hosting 8 facilities (Achebe, 2016).

Disruptions in the tantalum supply chain have occurred during the transportation of the beneficiated concentrate from mining countries to

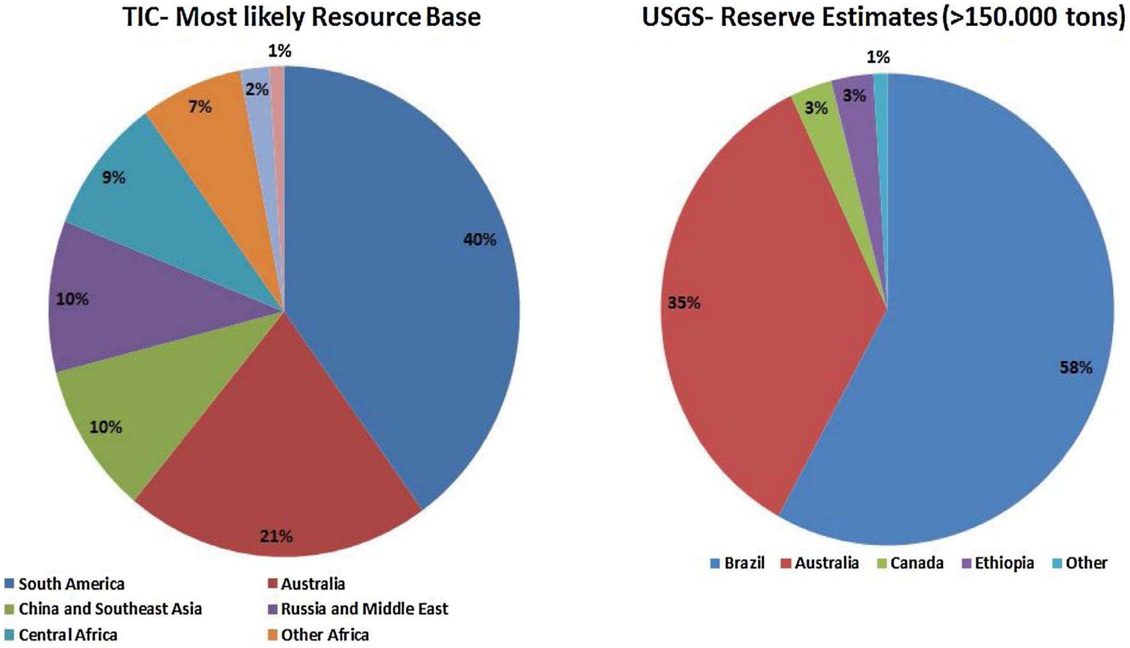

Fig. 1. Most likely resource base and reserve estimates of tantalum.
Source: Tantalum-Niobium International Study Center (TIC, 2016a); US Geological Survey (USGS, 2016).

processing countries caused by incidents such as theft, missing containers, logistical problems, and unaccounted and conflict minerals entering the global market. For example, tantalite mined in the DRC, is usually transported across porous borders into neighboring Rwanda or Uganda before being exported to overseas refiners (Moran et al., 2014). In recent years, Rwanda has become a major apparent producer with a large percentage of its exports being traced to the DRC (Bleischwitz et al., 2012; Nest, 2011).

Fig. 2 shows the share of tantalum usage by intermediate sector. The largest application (41%) is in the capacitor and semiconductor industry, where it is consumed in the form of tantalum powder. Tantalum content allows capacitors to be small and dense, making them valuable for size-constrained, high-performance electronic devices including laptops and mobile phones (Moran et al., 2014). A further 12% of

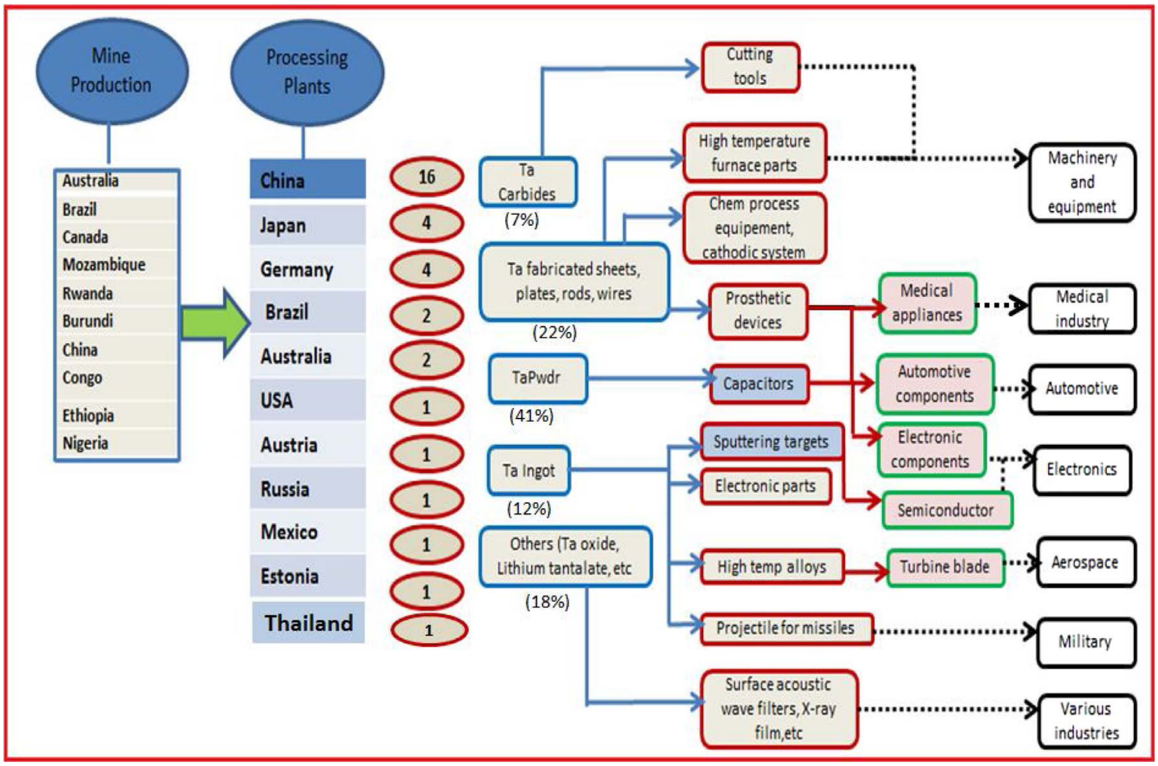

Fig. 2. Tantalum supply chain across upstream and downstream industries. The numbers inside the red circles are the number of major processing companies in different countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: Based on USGS, 2014a,b; USGS, 2016; BGS, 2011; and Deetman et al., 2017.

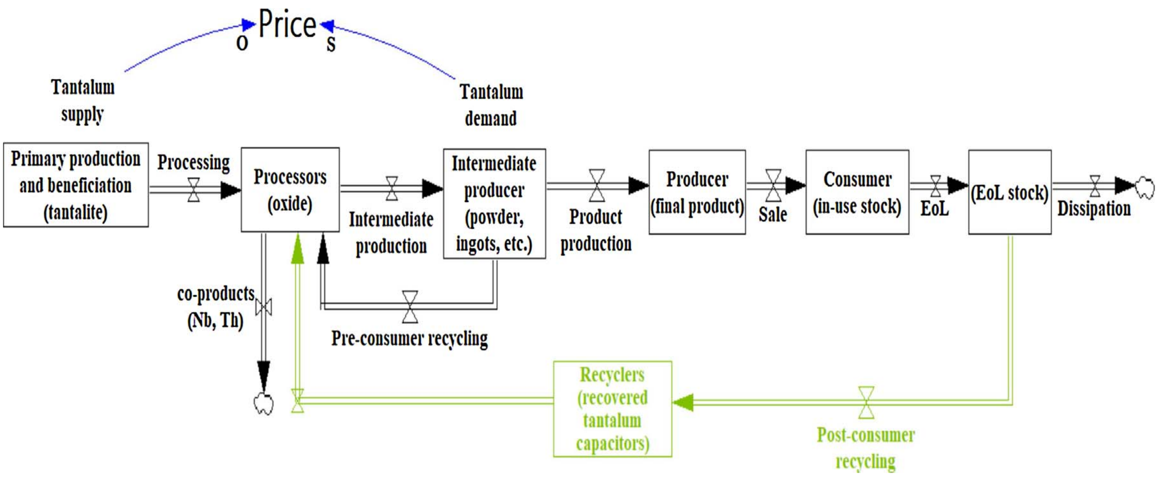

Fig. 3. The tantalum supply chain. Each box represents a stock of tantalum, while the form in which the tantalum is in that part of the supply chain is indicated between brackets. The arrows between the stocks represent physical flows of material. Green indicates stocks and flows that do not currently happen on a relevant scale (postconsumer recycling). The blue arrows represent how the elements in the system influence each other: the arrowheads indicate the direction of the influence, the S or O next to the arrowhead indicate whether the connected parameters change in the Same or Opposite direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tantalum is used in other applications in the electronics sector. Tantalum is highly resistant to heat and corrosion and therefore an important component in a variety of alloys and carbides, which are used in a range of specialized applications including electronic and medical devices, prosthetics, optical lenses, aerospace engines, and cutting tools.

2. Method and data

2.1. Resilience

Supply chains are complex systems with numerous actors and relations (Fig. 3). The development of resilience theory for supply chains of raw materials offers an effective theoretical framework for studying how systems responds to disruptions (short term disturbances) and constraints (long-term disturbances). For the supply chains of raw materials, resilience is defined as ‘the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available’. Conceptually, resilience is dependent on three factors (after Sprecher et al., 2015):

- Resistance: the system maintains its function (i.e., it is able to tolerate various types of disturbances without experiencing unacceptable loss of function).
- Rapidity: the system is able to rapidly recover so that it meets its goals again within a short period following the disturbance.
- Flexibility: the system is capable of meeting supply needs under a disturbance by switching between different (alternative) subsystems.

More concretely, the factors that contribute to resilience consist of (a) diversity of supply, (b) material substitution, (c) change of material properties, and (d) stockpiling.

In this work, we consider the entire tantalum industry (Fig. 4), including primary mine production, artisanal and small-scale mining (ASM), international trade, recycling rate and new investments in primary mining. We also consider a number of events that periodically affect the system, such as disruptions in production, changes in

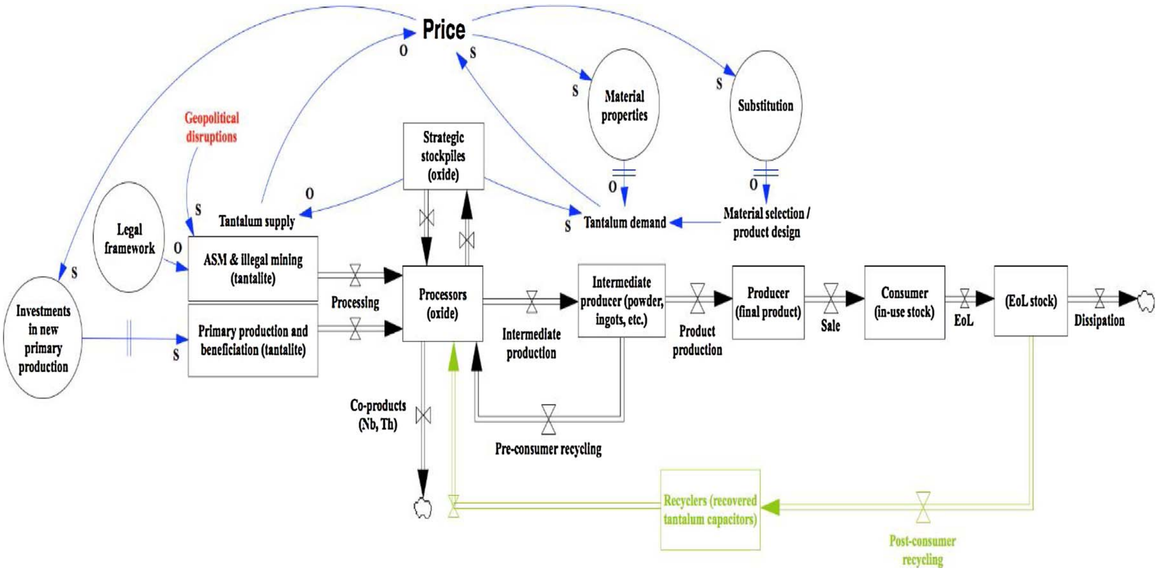

Fig. 4. The complete set of system dynamics in the tantalum supply chain, as found in this work. Compared to Fig. 3 the resilience mechanisms are added, and there is further elaboration of relationships between parameters.

Table 1
Concentration of tantalum in various intermediate products and pre-consumer waste and scrap.

Material	Theoretical value	Actual value
Tantalum carbide	93.7%	92.9%
Capacitor grade Tantalum powder		
– of EBM form	99%	99.6%
– of advanced particle form	96.8%	98%
Tantalum ingot	99.2%	99.8%
Mill product of Tantalum[a]	99.99%	99.9%
Metallurgical grade Tantalum powder	98.3%	99.4%
Tantalum scrap[b]		
– superior grade	99.0%	99.0% and more
– 1 st class grade	90.0%	90.0% and more
– 2nd class grade	20.0%	89.9%
TaW-2.5 alloy	97.5%	96.9%–97.4%
TaW-10 alloy	89.5%	89%–90%

[a] Ta mill products can be grouped together they are generally produced from the same starting material. These products are 100% the density of tantalum, surface area is negligible so oxygen is very low (less than 50 ppm). All other trace elements are also extremely low and usually certified as 99.999% pure.

[b] If its scrap tantalum capacitors its between 20 and 50% Ta, if its sputtering targets its 60%, if its scrap turnings its greater than 90%. Source: Interview with tantalum intermediate manufacturers.

government policies, technological shift and substitution, and price fluctuations.

2.2. Data collection

There are wide discrepancies in estimated amounts of tantalum produced, traded and consumed internationally (USGS, 2016; TIC, 2016b; BGS, 2011; Achebe, 2016; Bleischwitz et al., 2012). Our analysis highlights this mismatch in production and trade with particular attention to African countries. Our analysis is based on the data from sources including USGS, TIC and UN Comtrade database, and incorporates information obtained from companies through personal non-structured interviews and email communications. We use physical quantity rather than economic value to discuss tantalum production and trade to avoid bias associated with monetary valuation and price volatilities.

Based on the tantalum concentration data presented in Table 1, we estimated the global flow of total tantalum contained in intermediate products, waste and scrap, and capacitors. We also made a number of assumptions to estimate the global tantalum trade, in order to disaggregate data from UN-Comtrade, which groups concentrates of tantalum, niobium and vanadium under code 2615.90 in HS classification. We estimate tantalum quantity by deducting the possible niobium content with a factor of 0.25 for the Central African countries based on the concentration data of niobium and tantalum provided by the USGS mineral yearbook. We cross checked and try to match the production data of these three elements with trade data and make sure that either niobium or vanadium is not included in the data set inadvertently. We also considered the reported data of importing countries, which seems a more accurate approach than using the export data, given that many of the tantalum producing countries in Africa do not report their export reliably. We estimate the unaccounted African production by deducting the quantity of primary mine production (officially reported) from the global trade data of tantalum articles, assuming that tantalum articles are close to 100 percent tantalum (Table 1).

3. Results

The basic resilience framework and different mechanisms that underpin rapidity, resistance, and flexibility in tantalum supply chain are shown in Fig. 4. In following subsections, we discuss the factors that influence resilience in the system and how the system recovers from disruptions.

Fig. 4 shows the dynamics of tantalum supply chain. The price mechanism acts as an overarching feedback loop. Increased demand causes an increase in price, while increased supply influences the price negatively. Price fluctuations are discussed in Section 3.1. An increase in price also positively influences investment in primary mining (Section 3.1), diversity of supply (Section 3.2) recycling (Section 3.3), and substitution (Section 3.4). Stockpiling material can act both stabilizing and destabilizing (Section 3.5). Finally, the legal framework surrounding tantalum is of particular interest given considerations of tantalum as a conflict mineral (Section 3.6).

3.1. Overarching feedback loop: pricing and price fluctuations

Although reliable data for prices before 2000 are hard to come by, conflicts in Central Africa combined with increasing demand from the capacitor industry caused the tantalite price to sharply increase, peaking at US$350/lb in 2000. Efforts by industry to substitute tantalum in capacitors (Section 3.4) along with receding conflicts in Central Africa led to a drastic decline in price in following years. In this section, we discuss mechanics of tantalum pricing, focusing on the peak of 2010 and the period leading up to that.

We note that pricing is quite opaque. Unlike many other metals, tantalum is not openly traded on an exchange. There are two principal pricing mechanisms: long-term contract prices and spot prices:

- Long-term contracts are where price is are negotiated between buyer and seller and generally remain confidential. Exchange of this type is common among the conventional (LSM) miners and established companies in the downstream industry. Volatility may result in shorter-term contracts, in particular if the market power of suppliers is strong.
- Spot prices typically encompass lower prices than the long-term contracts. Certified conflict-free material comes with an additional premium. Much of the supply from ASM production in Central Africa is traded into the spot market, and spot prices are relatively volatile.

In the decade prior to 2010, prices remained stable and below US $40/lb, with small fluctuations prior to and after the global financial crisis of 2007–2008. Then, around 2010, a major price peak caused significant disruption in the tantalum supply chain.

Fig. 5 shows the tantalite price over the period 2002–2016. In early 2010, prices rose rapidly as global economic conditions improved and inventories such as the US Defense Logistics Agency stockpiles became depleted. Moreover, the Dodd-Frank Act became effective on July 21, 2010 and prompted companies to cut their dependence on non-certified sources. This increased the perceived supply risk in the industry. By early 2011, prices were three times higher than the previous year.

Once spot prices started to reach US$110-125/lb and contract prices were around US$150/lb, the LSM companies GAM and Noventa restarted production at their Australian mining sites (Stratton and Henderson, 2012).

Increased supply from ASM in Africa with a moderate demand from the downstream industry in 2011 caused the average price to decline from US$110/lb to about US$95/lb by year-end. The price of tantalum oxide (Fig. 5) also started to decline, from US$500-550/kg in June 2011 to US$270-300/kg in January 2016.

These price declines forced many large mines to close. Fig. 6 gives an overview of status of major tantalum mines as of 2017. GAM suspended production at its Australian Wodgina mine in January 2012. At its peak, this mine produced almost 700 tons per annum, about 25–35 percent of the world supply. The Kenticha mine in Ethiopia suspended its operations in May 2012. The mine had been one of the major producers of tantalum, contributing, with an annual production capacity of 275 tons, almost 14 percent of the world supply. Kenticha was closed

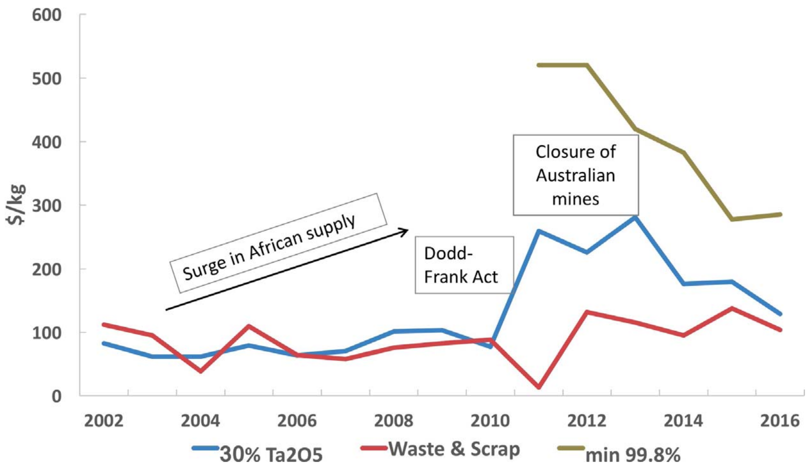

Fig. 5. Tantalum price fluctuations and major related events. Ta_2O_5 prices are generally given in $/lb. In this figure all prices are converted to $/kg to aid comparison. Waste and scrap price is the average import price calculated on a yearly basis of the total global import and value.
Source: Argus-metal pages, 2016.

both due to declining prices and the high cost of processing by-product radioactive mineral. Other major shut downs in 2013 were the Tanco mine in Canada, operated by the Cabot Corporation and the Marropino mine in Mozambique, owned by Noventa, a British company. Marropino had a maximum capacity of 225 tons per annum. The Tanco mine faced declining ore grades as it reached the end of its operating life, after operating for almost 40 years with an annual capacity of 175 tons and supplying almost 4 percent of the world supply.

A renewed dispute in the DRC in late 2012 caused a short-term recovery in prices. However, since, 2013, the market has witnessed declining prices across all minerals, including tantalum. There are several factors keeping the tantalum prices at low levels. Demand from the downstream industry is not strong enough to push the price up, since demand from the electronic industry has leveled. Only moderate growth is expected from advanced technology end-users such as the aerospace sector. As a result, owners of tantalum mines have been reluctant to increase output or re-open mines.

Interestingly, the closing of LSM facilities at Wodgina, Kenticha, Tanco and Marropino had no impact on prices since buyers were optimistic that additional certified conflict-free supply would be available from Africa.

Fundamentally, low prices make many mining projects financially less viable. This positive relation between price and new investment is depicted in our basic resilience framework provided in Fig. 4. Investments in new and potential tantalum projects across countries have been suspended or placed on hold in response to the decline in prices along with the increased supply from artisanal miners in Africa. Most of the mining companies in the tantalum industry are small players and declining tantalum prices have further forced companies to suspend production, sell off assets, etc., and a number of tantalum mining projects (see Fig. 6) are on hold as investment has become increasingly scarce.

Low prices have depressed capital expenditure (capex) in the tantalum sector as investment companies take a 5–10 year view while assessing short-term weakness. Fig. 7 illustrates the strong correlation between exploration budgets and nonferrous metal prices, which have been declining since 2011. According to SNL Metals & Mining, the industry's total budget for nonferrous metal exploration was US$9.2 billion in 2015, less than half the level in 2012. Investors are constrained by risk perceptions of financing, and greenfield investment (foreign investments in new operations) are generally unpopular in the stock market when prices are low.

Table 2 shows the expense of tantalum mining and processing cost for large scale producers. LSM projects are often based in areas of the difficult rock types, making it hard to mine and process compared to alluvial or soft rock ore types in Central Africa suitable for low-cost ASM mining.

Comparing the costs in Table 2 to the price of tantalum in Fig. 5 indicates that as of mid-2015, if spot prices are used as reference, most conventional tantalum mines operate with a negative margin and are probably compensated by co-production of other metals. There are several examples of polymetallic mines that co-produce tantalum. The tin industry produces tantalum from the tin slag by-product of the smelting of cassiterite concentrates. Other examples include struverite concentrates (a Ti-Nb-Ta mineral containing 9–12 percent tantalum oxide being produced in northern Malaysia) (TIC, 2016a), tin-feldspar

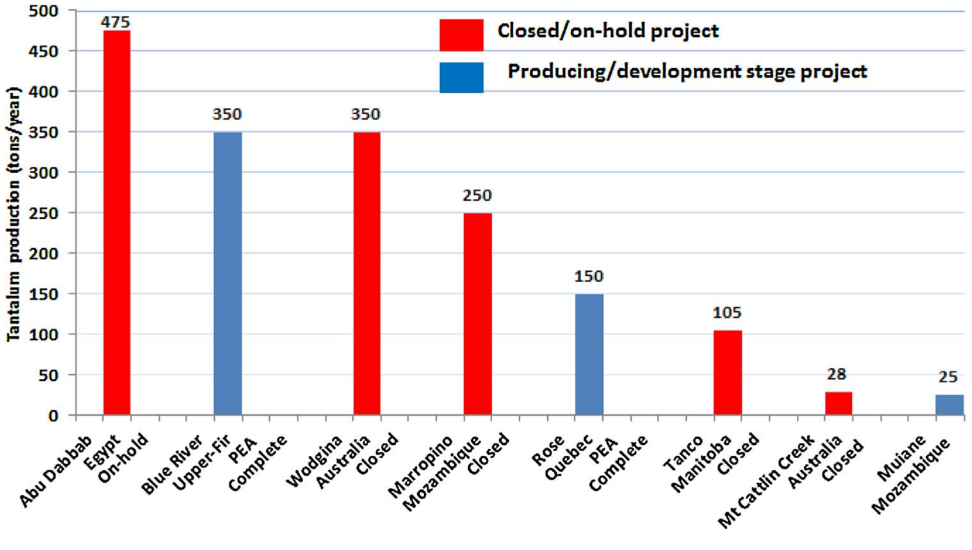

Fig. 6. Tantalum projects by mine circa 2017, classified as development stage or closed/on-hold projects, ranked by possible mineral production.
Source: Information compiled from company websites and market research firms.

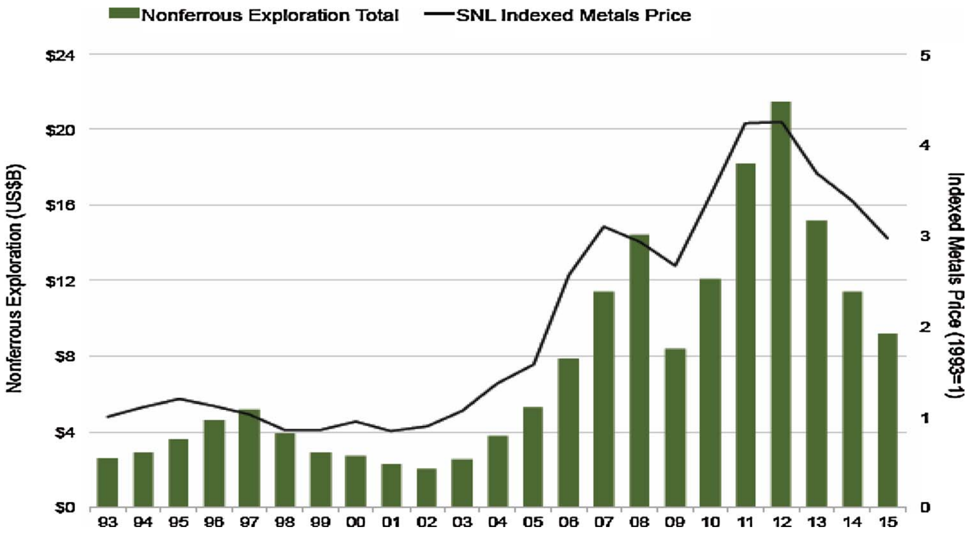

Fig. 7. Estimated global nonferrous exploration budgets, 1993–2015.
Source: SNL Metals and Mining, 2016.

Table 2
Estimated average operating cost of a hard rock mine. Cost calculated for the primary mining operation of a hard rock mine and production of tantalum oxide.
Source: based on interviews with mining and processing companies.

Cash costs	Cost per Tonne Milled ($/t) (1/2 lb Ta/ton)	Cost per Kg Ta_2O_5 ($/kg) payable
Mining	20	170
Process	14	110
Material Handling	0.70	26
G & A	2.00	6
Total	36.7	312

(for projects in Southeast Asia and Egypt), niobium (for projects in Brazil and Canada) and lithium (for Australia). Finally, it should be noted that outputs from mines in Brazil are usually exported to US and Europe under long-term contract prices. Thus, their operations are not affected by price fluctuations until contracts are renegotiated.

3.2. *Diversity of supply: primary production of tantalum ores and concentrates*

Analyzing the exposure of primary tantalum supply to disruptions is complex because of a lack of data on production and trade and the mismatch between production data and trade data, as well as a general lack of transparency in minor metal industries. Artisanal mining in Africa adds further complications. Although ASM can contribute to primary supply in a legal and formal way (Stratton and Henderson, 2012), artisanal mining from the eastern part of the DRC is the origin of conflict tantalum and significant amounts appear not to be accounted in official production statistics. First, we will look at which countries contribute most to global tantalum supply (3.2.1), then we focus on 2014 as a reference year to explore tantalum flows in more detail (3.2.2).

3.2.1. *Evolving tantalum supply over time*

Rwanda and the DRC are currently the leading global producers of tantalum mineral concentrates. On the basis of USGS primary production data and UN Comtrade data on trade in tantalum articles, we calculated the total production of tantalum, both accounted and unaccounted (assumed to be illegal African artisanal supply). We found that in 2014, officially reported primary production (which takes into account conventional mines, legal ASM ores in Africa and tin slags) was around 1200 metric tons (USGS, 2016). The total amount of tantalum contained in products was closer to 3500 metric tons.

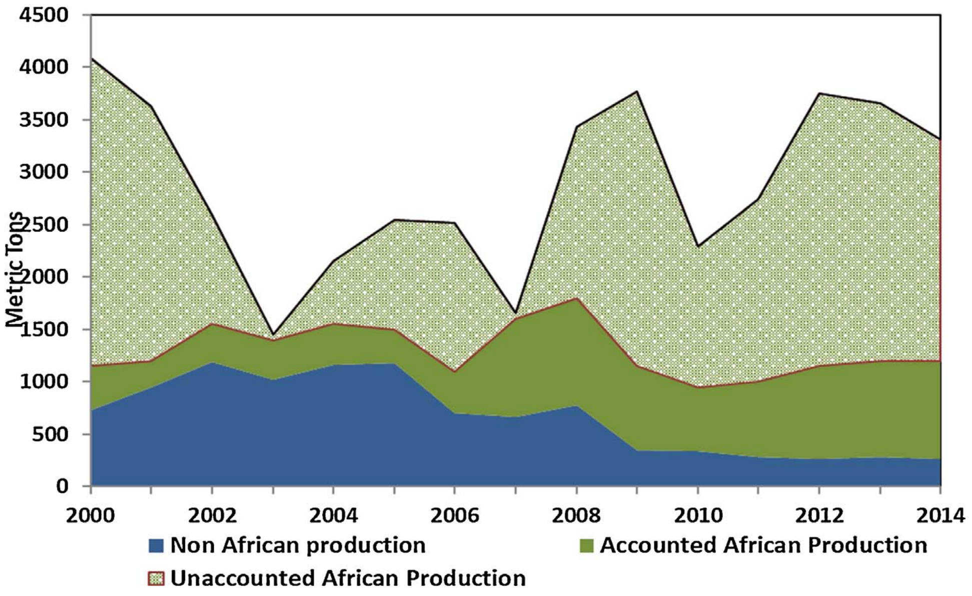

Fig. 8. Primary production versus unaccounted African production. Data on production include only tantalum ores and concentrates.
Source: calculated on the basis of USGS data on primary production (USGS mineral yearbooks, 2000–2016) and UN Comtrade database on trade in tantalum articles.

Results are shown in Fig. 8, which illustrates that before the 2008 financial crisis there was a relatively significant production of tantalum outside of Africa, and that Africa's production of certified tantalum shows an increasing trend. On the basis of trade figures and the analysis presented here, we find that Africa today provides more than 80 percent of the world supply, with a large portion of this production not considered by either USGS or TIC in their tantalum production statistics. Unaccounted supply from Africa is for a large part suspected of being conflict minerals transferred across borders. In fact, actual unaccounted production in Africa might be even higher than our estimation, as we did not consider the global trade in tantalum oxide and pre-consumer waste and scrap along with production intended for domestic consumption, particularly in China (Fig. 11).

3.2.2. Global tantalum flows in 2014

As detailed in the previous section, 80% of global tantalum is sourced from Africa, where a zone of Neoproterozoic-age tantalum-mineralized pegmatites cuts through the Mezoproterozoic Kibaraan belt, which extends through Burundi, Rwanda, Uganda, and the DRC. Ore is mined both from deeply weathered pegmatites and from secondary placer deposits derived from the pegmatites (BGS, 2011). Concentrate from Africa is relatively low-cost given ASM production, and thus outcompetes conventional mines in Australia and Canada, many of which closed in the aftermath of the 2009 financial crisis. We note that a small portion of tantalum is still produced in Australia as a byproduct of lithium mining. Brazil, which has the second largest reserves, maintains a steady supply despite the low prices. China, too, has constantly been increasing its domestic production, increasing to about 60 tons in 2015. The dependence of global tantalum industry on low-priced African resources affects the resilience of the tantalum supply chain and leaves supply prone to major disruptions. In the following section, we focus on 2014 as a reference year to further explore exactly what global tantalum flows look like across the value chain.

Exploring the data underlying Fig. 9 shows Brazil's exports of 940 tons, which is comprised of both tantalum and niobium, as more than 90 percent of niobium is mined in Brazil (USGS, 2016). While most of the niobium is processed within Brazil (Abraham, 2015), there is a chance that a small portion of concentrate is exported abroad. The US shows some exports, which we believe to largely comprise of vanadium ores and concentrates. Surprisingly, Hong Kong is statistically a major exporter of tantalum concentrate. In this case, the port most likely functions as a transit point to mainland China.

The reported data for year 2014 shows that Rwanda produced 600 tons, the Congo 200 tons, Nigeria 60 tons, Mozambique 85 tons, and Burundi 14 tons of tantalum concentrates (Fig. 10). The DRC did not report the export of any tantalum in 2013 or 2014. However, the import data of other countries shows 517 tons of tantalum being imported from DRC. More significantly, both the Comtrade export statistics and data reported by Rwandan press quoting National Bank of Rwanda show that Rwanda exported 2466 tons of tantalum in 2013 (KT Press, 2014), which contrasts strongly with its reported production of 600 tons. The most likely explanation is that a major share of tantalum exported from countries like Rwanda and Uganda is mined in the Congo by rebel groups and smuggled across the border (BGS, 2011; Nest, 2011). If we assume that all "missing" tantalum production stems from unofficial ASMs in Central Africa, the overview of tantalum sourcing and trading from African countries would look as presented in Fig. 10.

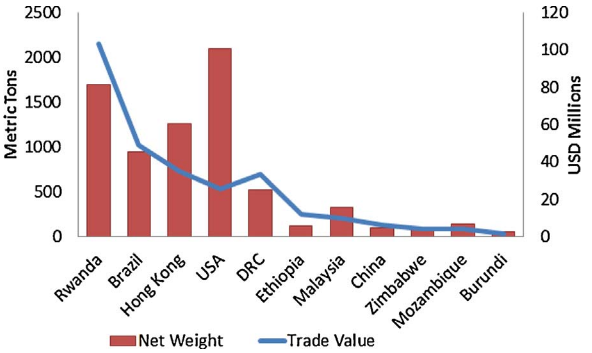

Fig. 9. Top 10 exporters of tantalum ores and concentrates (HS.261590) in 2014. Source: Estimated on the basis of national data reported to UN Comtrade, 2016.

Fig. 10 shows that a major portion of the unaccounted material goes to Chinese smelters, which is supported by other analysts (Stratton and Henderson, 2012). In Fig. 11, we track Chinese exports of tantalum containing materials. As shown in Fig. 2, China has the largest number of tantalum processing companies and is a major producer of tantalum-based intermediate and final products. Most material is exported to other countries in the form of tantalum waste and scrap, tantalum intermediate products and tantalum capacitors (Fig. 11).

3.3. Diversity of supply: current status and prospects of recycling

Recycled tantalum contributes almost 30 percent of the total supply. This share has increased continuously over the years. We differentiate between post-consumer and pre-consumer recycling. Post-consumer recycling increases the diversity of supply because it can complement primary production and provides an alternative means of obtaining material (Deetman et al., 2017; Sprecher et al., 2014; Schulze and Buchert, 2016). Pre-consumer recycling does not count towards improving diversity of supply, because it usually consists of internal recycling loops within industry as a result of inefficiencies present in manufacturing processes (Sprecher et al., 2015).

Despite significant potential (Nassar, 2017; Deetman et al., 2017), a limited amount of tantalum is recycled from end-of-life products. The tantalum concentration in consumer finished products is usually tiny, and subject to pulverization during dismantling processes, along with high upfront transaction and investment costs for establishing a collection and dismantling system, thus making post-consumer recycling uneconomical (Bleischwitz et al., 2012).

Tantalum is recycled mostly from pre-consumer scrap generated during the manufacture of electronic components, cemented tantalum carbides, and super-alloys. Tantalum scrap generated during the production of intermediate products has a high purity and is easy to collect and re-melt directly, and therefore gets fully recycled.

Pre-consumer recycling plays a special role in the tantalum system. Well-established methods of pre-consumer recycling and recycled tantalum receive the conflict-free status. Trade in recycled tantalum is largely transparent as it is conducted between established smelters and refiners. To comply with conflict-free tantalum regulation, the US and the EU are increasingly trading in recycled tantalum. As mentioned before, the US has about 11 tantalum refining companies and their production input is largely intermediate chemical compounds, crude metal forms, and scrap material. The US and Mexico account for 61 percent of the scrap recycling (Achebe, 2016). In contrast, the main feed stock to Chinese tantalum smelters is mineral concentrate and other tantalum primary raw materials (Achebe, 2016).

Fig. 12 shows the increasing quantity of trade in tantalum waste and scrap. 1200 metric tons were traded in 2014, almost equal to the primary production of tantalum. To generate this amount of scrap at steady recycling rates, primary production has to keep pace. Instead, primary production has dropped with closures of many industrial mines, corroborating the increase in the unaccounted production in Africa as found in Section 3.2. This data gap is acknowledged in statistical figures provided by TIC in their bulletin 164, January 2016, (TIC, 2016b).

Fig. 5 shows the trend in average price per kg of recycled tantalum from 2002 to 2016, which reflects the price fluctuations of tantalum concentrates and overall metal price trends (Fig. 7). As in the case of primary ore mining and processing, the recycling of a product also relates to its market price and the mixture of materials used in a

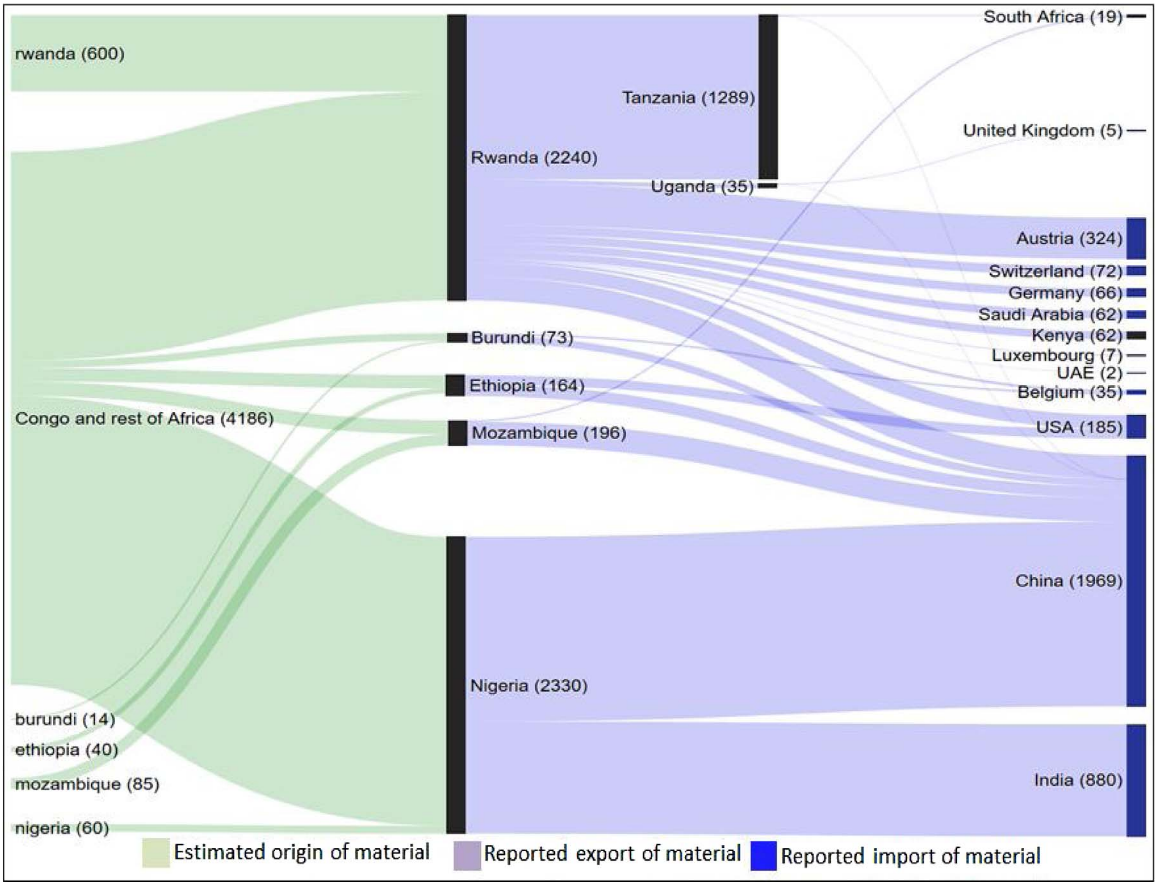

Fig. 10. Tantalum flow from Africa in 2014. Numbers in brackets show the production and trade quantities in metric tons. The figure reconciles data on production and exports from African countries by assuming that all missing tantalum production stems from the DRC and rest of Africa. The Sankey diagram depicts flows of tantalum, where the width of each flow pictured is based on its quantity. We assume about 25 percent of niobium content in the export figures.
Source: Estimate based on USGS, 2016; USGS, 2014a,b, and UN Comtrade data, 2016.

particular product. Thus, the current market price and the value of other trace elements in the product determine the economic viability of recycling (Bailey et al., 2017). Interestingly, comparing prices of tantalum concentrate and tantalum scrap prices shows that for most of the years since 2002, scrap has been priced lower than the tantalite, and since 2011 this gap has grown wider. For example, in 2014 the average price for tantalite was around US$180/kg whereas the average price for tantalum scrap was around US$95/kg.

It is somewhat surprising that high purity industrial scrap is priced much lower than concentrate (30% Ta_2O_5). One explanation is that the concentrate price shown in Fig. 5 is the spot price of tantalum supplied from conventional primary mines, which contributes less than 50 percent to the total world supply, while the balance is supplied by artisanal miners in Africa at much lower prices.

In Fig. 12 we provide a forecast of recycled tantalum volumes, based on a ‘business as usual’ scenario (i.e. average growth rate of the last five years, no new discovery of alluvial soft rock deposits outside Central Africa, no increased conflict in Central Africa, and no government interventions through mechanisms such as quotas, taxation, or stockpiling). This shows that by 2025, there will be more than 1600 metric tons of tantalum supply from pre-consumer recycling, contributing more than 50 percent to the global supply.

Increased supply from recycled sources shows flexibility in a resilient system and in the case of tantalum, the role of recycling is expected to increase further. Through this increasing dependency on recycled material, the system is capable of meeting supply needs when there are disturbances (e.g., certification and compliance issues and reduced primary supply) by switching between different (alternative) subsystems.

3.4. Substitution

Although tantalum capacitors constitute less than 10 percent of the overall capacitor market, almost 50 percent of the tantalum supply is used by the capacitor industry, making tantalum prices very sensitive to the demand from the capacitor industry (Vulcan, 2009). Therefore, we focus on substitution of tantalum capacitors.

To address cyclical shortage and price spikes of tantalum, the electronics industry asked capacitor manufacturers for substitutions. Based on interviews we found that material substitution took on average one year to implement. This relatively fast substitution rate was due to the fact that alternative capacitor technologies already exist for other applications. Smaller tantalum capacitors were substituted by multilayer ceramic capacitors (MLCCs). Larger tantalum capacitors were replaced by aluminum capacitors. In low equivalent series resistance (ESR) applications polymer aluminum, and in some cases niobium capacitors, can be utilized (Nakatani, 2010; Vrana and Reynolds, 2002).

Receding conflicts in Africa and substantial substitution occurring from late 2001 onwards contributed to a decline in tantalum price. In response, companies restarted their use of tantalum capacitors, even though aluminum and ceramic capacitors were found to have superior performance in certain applications (Gervasi, 2012). This illustrates how substitution is a two-way street between alternative technologies. In this case, the industry responded in a rapid way to meet the supply shortage and consequent price rise by turning to alternate subsystems.

Many alternate technologies have their own limitations and are not as efficient as tantalum capacitors. For example, the diffusion rate of oxygen from the dielectric to niobium metal is higher compared to

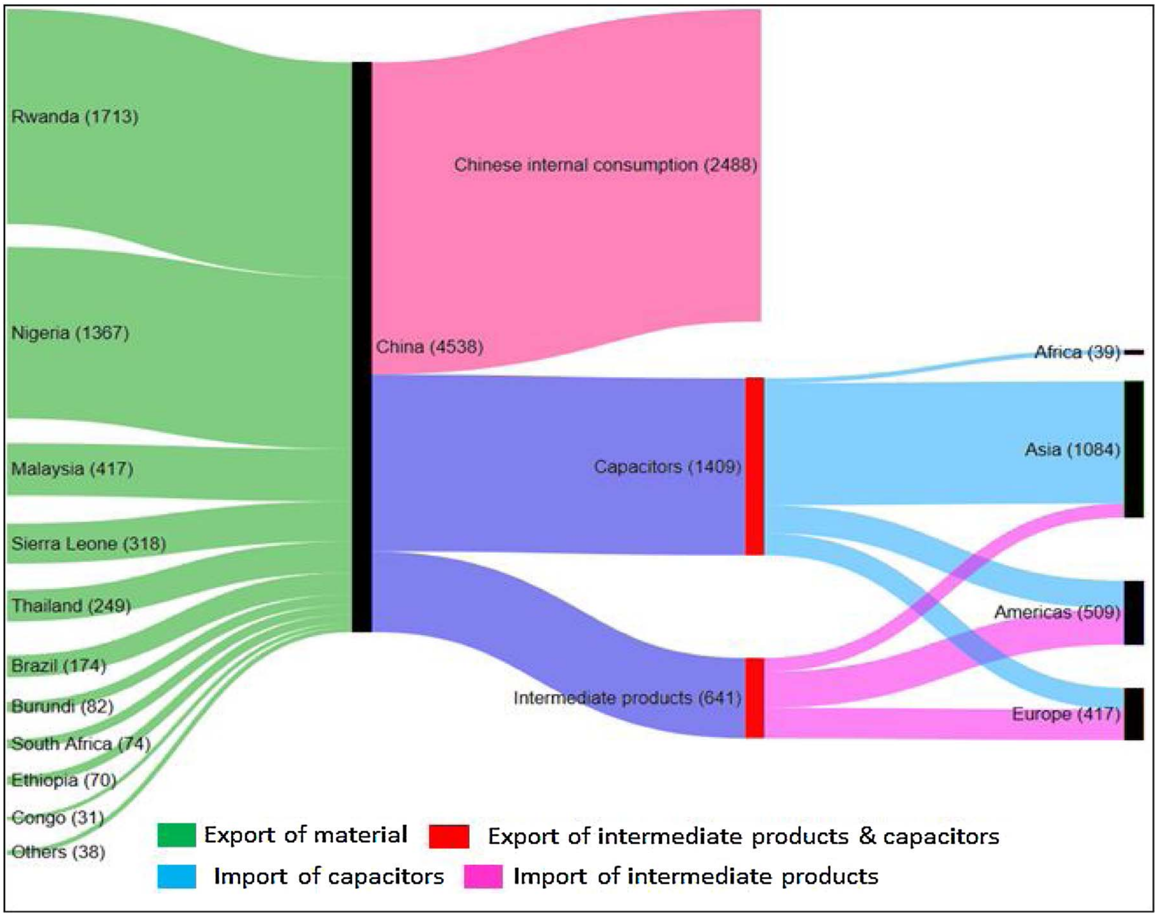

Fig. 11. China's import of tantalum concentrate and export of tantalum intermediate products and tantalum capacitors (in metric tons).
Source: Estimate based on UN Comtrade data, 2016.

tantalum, resulting in DC leakage (DCL) instability. Historically, there was also a lack of high purity niobium powder to meet the specifications of capacitor manufacturers (Freeman et al., 2012). In the case of MLCCs, they lose their capacitance properties after few years.

Fig. 13 shows trade in tantalum capacitors, and displays an inverse correlation between tantalum capacitor utilization and price. This is most apparent when the price increased sharply after 2010. Fig. 13 also reveals the substitution effect of a tantalum price change on increased trade in alternate technologies, MLCCs and aluminum capacitors. Demand for ceramic and aluminum capacitors has steadily increased, except in a few specific years such as during the global financial crisis. The trade quantity of MLCCs is on average five times higher and the average for aluminum capacitors is 10 times higher than the global trade of tantalum capacitors.

We note that trade comparisons based on weights of different types of capacitors should be seen as indicative, as we recognize the limitation of this comparative analysis. Capacitors range from cupboard sized to micro components for integrated circuit boards. The type of material used impact the charge held per surface area of the material, thereby affecting the weights as well. Capacitors are also used in power electronics, for instance, as a start capacitor in an electronic motor, and specific types of capacitors are used for larger applications.

3.5. Stockpiling: strategic and company level

As illustrated in Fig. 4, building up a significant stockpile can cause a surge in demand, and hence increase price. Release of an existing stockpile creates supply and consequently negatively influences price.

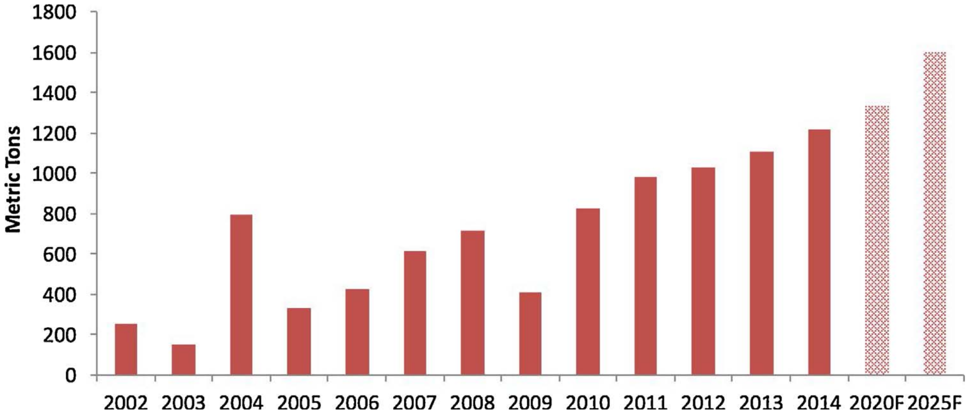

Fig. 12. Trade in tantalum waste and scrap, and projected quantity of trade in tantalum waste and scrap for 2020 and 2025 in a business as usual scenario.
Source: Estimate based on UNCOMTRADE data, 2016.

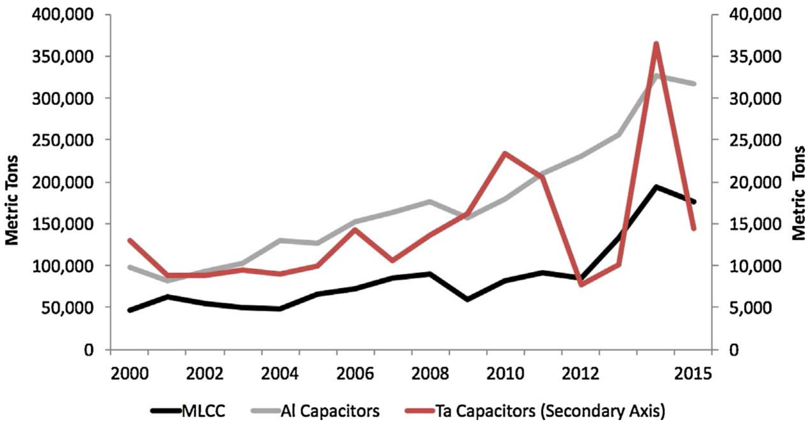

Fig. 13. Global trade in tantalum, multilayer ceramic, and aluminum capacitors.
Source: estimated on the basis of the UN Comtrade data using a unit conversion factor to calculate the total weight as the Comtrade database provides trade quantity in kg weight for certain countries and number of items (units) for others.

In the case of rare earth elements, Sprecher et al. (2015) observed that urgent stockpiling during a supply crisis can drive up the price significantly, fueling the perceived threat of supply disruption. This leads to a positive feedback loop associated with emergency stockpiling by manufacturers and speculators.

Inventories of tantalum held by companies throughout the supply chain are a significant factor in determining tantalum prices and the demand for primary tantalum. In order to negate the impact of any temporary supply disruption, the major tantalum intermediate producers (e.g., Cabot and HC Starck) follow a policy of stockpiling tantalum. It is estimated that some industry inventories are sufficient to last for two years (Stratton and Henderson, 2012). This is in line with findings from Sprecher et al. (2017) for REE stockpiles held by producers of intermediate neodymium-magnet products.

Perceived supply shortages in the 1990s prompted the US government to stockpile tantalum. At its peak, the Defense Logistics Agency (DLA) stored around 1200 tons of tantalum, which was greater than the global supply at that time (Fig. 14). While we could not find hard data, due to the significance of the stockpile build-up one may assume that this contributed to driving up the prices. When the situation normalized several years later, DLA started to release its stocks. In that period, the US government was the second largest seller of tantalum (at 175–300 tons per year). The DLA exhausted its stocks of tantalum metal ingots in 2005, metal powder and metal oxide in 2006, and minerals in 2007. However, the DLA does still hold a few tons of tantalum carbide powder and tantalum metal scrap in its inventory (USGS, 2014a,b).

3.6. Legal framework

Processors, smelters, and producers of tantalum intermediate products are encouraged to follow OECD due diligence guidelines and the United Nations (UN) Guiding Principles on Business and Human Rights related to conflict minerals (OECD, 2013; UN, 2011). If operating in the USA, they are also obliged by law to report on sources of conflict minerals, and prefer not to purchase from uncertified supply-chains. Apart from governmental initiatives in US and EU, there are also several programs run by industry with the help of international NGOs and local governments in Central Africa. These initiatives are referred to as "bag and tag," which essentially means identifying tantalum ore at the source of its production and providing a means to track it along the supply chain to the smelter (Young, 2015; Stratton and Henderson, 2012). The objective of these initiatives is to provide assurance of conflict-free sourcing of minerals (including tantalum) contained in the final products, based on a chain-of-custody to their original source, and thus to prevent illegitimate minerals being used (Young and Dias, 2011).

Among the major tantalum-related initiatives are the iTSCi and the conflict-free smelter program (CFSP) developed and driven by the Electronics Industry Citizenship Coalition (EICC) and the Global e-Sustainability Initiative (GeSI), and recently shifted to the Responsible Minerals Initiative. These programs have their own limitations, as there are inherent risks in supply-chains, such as legitimate tags being sold to illegal producers or theft of mineral, enabling continued markets for conflict tantalum. Notably, neither CFSP nor iTSCi have a system of collecting and maintaining the statistics on quantities of certified minerals, even though most of the tantalum consuming industries and a growing number of tantalum smelters and traders are part of these initiatives. China, the main consumer of African minerals and the largest producer of tantalum based intermediate products, has shown less interest in these initiatives in the past. However, as of 2016, the CFSP claims that all Chinese smelters except one have obtained EICC-GeSI conflict-free smelter certification.

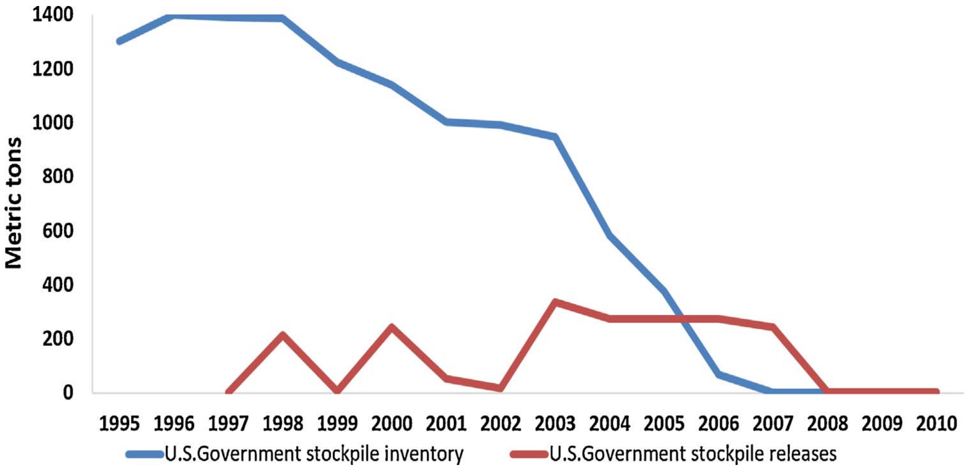

Fig. 14. US tantalum stockpile inventory and releases.
Source: USGS mineral commodity (tantalum) summaries 1995–2012.

Based on interviews with representatives of the industry, we found that conflict-free Ta concentrates generate a price premium at the smelter level. Conversely, the prices in China for K-salt (K2TaF7) and tantalum pentoxide (Ta2O5) or intermediate products, like tantalum carbide, metal, and ingot are much lower than in other countries, implying inadequacy of these frameworks to cover China. However, we are unable to provide any information as a reference or baseline for comparing contract or spot prices among the following:

(1) certified Ta concentrate shipments from Central/East Africa (according to the CFSP/iTSCi schemes);
(2) non-certified (non- CFSP/iTSCi) shipments from Central/East Africa;
(3) shipments from outside Central/East Africa (countries not covered under the Dodd-Frank regulations, hence with no regulatory due diligence reporting requirements).

There are price differentials among these different shipments/supply chains. Based on current data it is not possible to conclude whether these differences reflect an actual price premium being paid for shipments from any of these categories, or whether they effectively correspond to a price penalty for non-certified materials.

Additional measures to ensure conflict-free material may result in a supply shortage of major compliant sources of conflict-free tantalum with corresponding price increases. This happened in 2010, when the introduction of the Dodd-Frank Act prompted companies to cut their dependence on non-certified minerals, and the price increased based on a perceived supply risk in the industry.

4. Discussion on the relevance for market actors and policy dimension

There are very few studies that have dealt with the tantalum supply chain in its entirety. This study fills this gap keeping the price at the center as an overarching feedback loop and its relations to various resilience promoting mechanisms such as diversity of supply, recycling, stockpiling and legal frameworks. In the process, we quantified the unaccounted tantalum supply from ASM sources and its impact on the resilience. Applying resilience to the entire supply chain is considered as a dynamic (i.e. time-dependent) approach and we consider this as a strength of the paper.

We find that, while participation in conflict-free sourcing has reached substantial levels, unaccounted tantalum flows are still significant. The Dodd-Frank Act and other voluntary requirements had only a short-term impact on pricing. Similarly, we do not expect the European enactment of legislation to have any considerable long-term impact. However, such legislation may bring more transparency to the industry, strengthening system resilience and helping ASMs in Africa integrate into the mainstream supply chain. Over the long term, strengthening the capacity for conflict-free tantalum in the market will likely push prices upward. Conflict-free tantalum sells at a significant premium, and is often sold via long-term contracts, which presents the possibility of large scale mines to re-open.

As shown in the analysis, the unaccounted production and illegal smuggling across borders in Africa and the primary production in conventional mines and investment in new projects are intertwined and dependent on each other. Oversupply from Africa, where labor is exploited without consideration for human rights or environmental concerns, makes African resources cheap in the short term and suppresses prices below what is considered sustainable (Frankel, 2016; Amnesty International, 2016). This necessitates strengthening the best mining practices in Africa and strengthening the certification system without affecting the livelihood of the thousands of people involved in artisanal mining in Central Africa. The development of a robust and modernized mining industry in Africa would reduce the price gap between the African materials and the rest of the world.

Although tantalum ores are currently widely available, the industry needs to foresee possible supply disruptions in Central Africa. A supply chain disruption would have a substantial impact on price. The ability of the market to adjust to this will depend on the time lag needed to restart suspended mining or to increase production at operational mines. The US strategic stockpile has depleted its tantalum stockpiles, and thus is not in a position to stabilize the market in case of disruption.

Like other minerals such as rare earth elements, China dominates in capability to process tantalum concentrates. There are few facilities outside China with the same capacity to produce various products across the full value chain, from processing the ore to making the final products (Mancheri and Marukawa, 2016). Refining and downstream industries based in industrialized countries, which largely depend on China for tantalum scrap and intermediate products, should take note of Chinese protectionism related to material exports (Mancheri, 2015; Tucker, 2014). In anticipation of such restrictions, the US and the EU initiated a first step in the WTO (World Trade Organization) dispute settlement proceedings against China in July 2016 over export restrictions on select raw materials such as antimony, cobalt, and tantalum (Dendrinou, 2016; ICTSD, 2016). This case is the third example of such legal action taken against China in the last five years initiated by the US and the EU.

The current industry practices are not sustainable in the long term. A practical implication of our work is that diversity of material supply is important; over dependence on unregulated Central African resources will keep prices below a sustainably profitable level, negatively affecting the primary mine operations and new investment in formally regulated and certified producers.

It is our hope that a resilience based supply chain assessment of a conflict mineral sheds light on ambiguous practices in the industry. Greater system transparency is necessary to improve sustainability of the industry and this needs to include a rigorous revision of how data are reported, particularly at the upstream production stage. A limitation of this study is that due to the lack of official data we relied upon implied data. We were also unable to differentiate between certified and non-certified tantalum prices. For future research, a detailed analysis of tantalum flows at a global level, particularly using SFA methods, can provide knowledge about global flows related to production and sourcing practices, while also helping to fully quantify the resilient supply chain framework parameters.

5. Conclusion

This study highlights the huge data gap that exists between accounted production and the final consumption of tantalum. Our results reveal that Africa today provides more than 80 percent of primary world tantalum supply. We estimated a volume of more than 2000 tons in 2014, an increase of 250 percent from 2004 and 2014. The supply of smuggled tantalum from conflict regions has proven to be remarkably resilient in the face of legislative action such as the Dodd-Frank act. As was previously noted by Sprecher et al. (2017) regarding the illegal trade of rare earth elements, resilience is not necessarily a positive attribute, and has long term implications for the sustainability of the overall tantalum supply chain.

Our findings are summarized as follows. Although the ASM supply from Africa makes the system flexible, the domination of the ASM dependent spot market in tantalum sector is a constraint on system resilience as it negatively influences prices, and forms an overarching feedback loop. Declining metal prices cause lower profits for companies, which leads to lower investments in new primary production and reduced recycling. As a result of companies complying to certified tantalum, we find significant and increasing levels of recycling of industrial waste and scrap, as well as limited recycling of EOL products. Increasing use of recycled material illustrates how recycling contributes to the overall resilience of the tantalum supply chain, through switching between alternative sources of supply.

Price is also a determining factor in material substitution. When faced with shortages, the industry rapidly substituted alternative capacitor materials for tantalum, often within one year. This compared to the 2-year substitution time-lag found by Sprecher et al. (2017) for neodymium magnets.

Stockpiling of material – either by government or companies – may also prompt a price increase and the release of an existing stockpile increases supply and consequently reduces price as was found in this study. Nationally binding legislations, as e.g. the Dodd-Frank Act in US, prop-up demand for conflict-free material. We found a clear yet temporary price signal at the time of introduction of legislation. Global enforcement would provide more opportunities for conventional raw materials producers to (re-)enter the mining and refining market. Such measures also need to extend to downstream industries including the exchanges in pre-consumer waste and scrap, as recycling is now sometimes used as a route to convert illegal tantalum material to certified tantalum.

In the larger context, our analysis of the resilience mechanism shows that, historically, the tantalum supply chain has been very *flexible* in its response to disruptions and has recovered with remarkable *rapidity*. The imbalance in demand and supply and consequent decline in price is largely attributable to the over dependence of unaccounted materials from Central Africa traded below market price. However, price decline is also related to prevailing global market conditions, affecting the entire mineral sector. In this context, it would be very interesting to see future research applying this framework to the supply chains of major metals like steel, aluminum or copper.

Since this study is based on an inductive reasoning, by its nature, is more exploratory of each identified factors we believe this study will enable other researchers to build on the resilience approach and analyze more thoroughly the bottlenecks and disruptions in a supply chain of critical materials. This approach can also be applied to analyze other conflict minerals or precious metals, taking into account the entire supply chain system.

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