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The re-direction of small deposit mining: Technological solutions for raw materials supply security in a whole systems context



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ARTICLE INFO

Keywords:

Sustainability
Mining
Criticality
Ethics
Narratives
Technologies

Large-scale mining of low-grade ores is energy-intensive and generates vast wastes. It has limited suitability for production of specialist metals that are required in relatively small quantities. An approach that limits environmental impact by restricting mining to high-grade deposits requires the investigation of small ore deposits as alternative sources of metals. The return on investment from small deposits is incompatible with the expensive surveys needed to secure investment and the high costs of managing risk. But increasing energy and transport costs may create space in the market for small-deposit mining with highly-competitive technological solutions. It can be argued that small-deposit mining is ethical because it must involve cooperation between mining companies and local residents who share a collective expectation and responsibility for their quality of life. However, small-deposit mining tends to be a limited, short-term initiative, which requires consideration of the extended 'afterlife' of mines. This manuscript is the culmination of five years of cross-sector dialogue and stakeholder engagement activities. It debates what constitutes a small deposit and describes the interactions between mining and manufacturing, investment, environment and society. It reaches the conclusion that technological innovations will support the re-emergence of small deposit mining as an important part of a diverse raw materials production sector. We do not suggest a return to past approaches, to mining of small, high-grade deposits, but a consideration of alternative narratives of localised, community-orientated mining processes, thus giving social, economic and environmental context to the needs of the present day.

1. Introduction

The prices of major metals are closely linked to economic cycles. Thus, declining production is linked to falling demand rather than to the declining availability of geological resources (Graedel et al., 2014). The resulting scarcity of feedstocks drives prices upwards. This encourages investment and research into substitution, recycling, exploration and production technologies. Improved recycling methods have led to increased secondary supplies of metals. However, the relative contribution of recycled materials to feedstock supplies within circular economy framings, particularly of minor metals used for modern technologies, are limited. There are multiple underlying reasons: incremental losses of metals throughout the manufacturing chain; a lack of economically-competitive sorting and recycling technologies;

limited availability of end products to recycle; and global demand for end products is growing faster than the contribution from recycling (Fig. 1) (Oberle et al., 2019; Steinbach and Wellmer, 2010). Demand for primary raw materials therefore continues to increase. Fig. 2 shows annual global production of multiple metals from 1970 to 2015, for 10 commodities. Iron is mined in quantities that are two orders of magnitude greater than copper, aluminium, lead and zinc. Each of these bulk metals are in turn produced in volumes that are two orders of magnitude greater than antimony, tungsten, Rare Earth Oxides (REO), cobalt and bismuth. With the exception of bismuth, the rate of primary production for all commodities is accelerating. (The data for bismuth includes primary production, i.e. Núi Pháo mine in Vietnam, and the by-product of tungsten and lead mining, primarily from China). Fluctuations in demand and supply affect the metals that are produced in

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<https://doi.org/10.1016/j.rcrx.2020.100040>

Received 19 March 2020; Received in revised form 5 June 2020; Accepted 9 July 2020

Available online 11 July 2020

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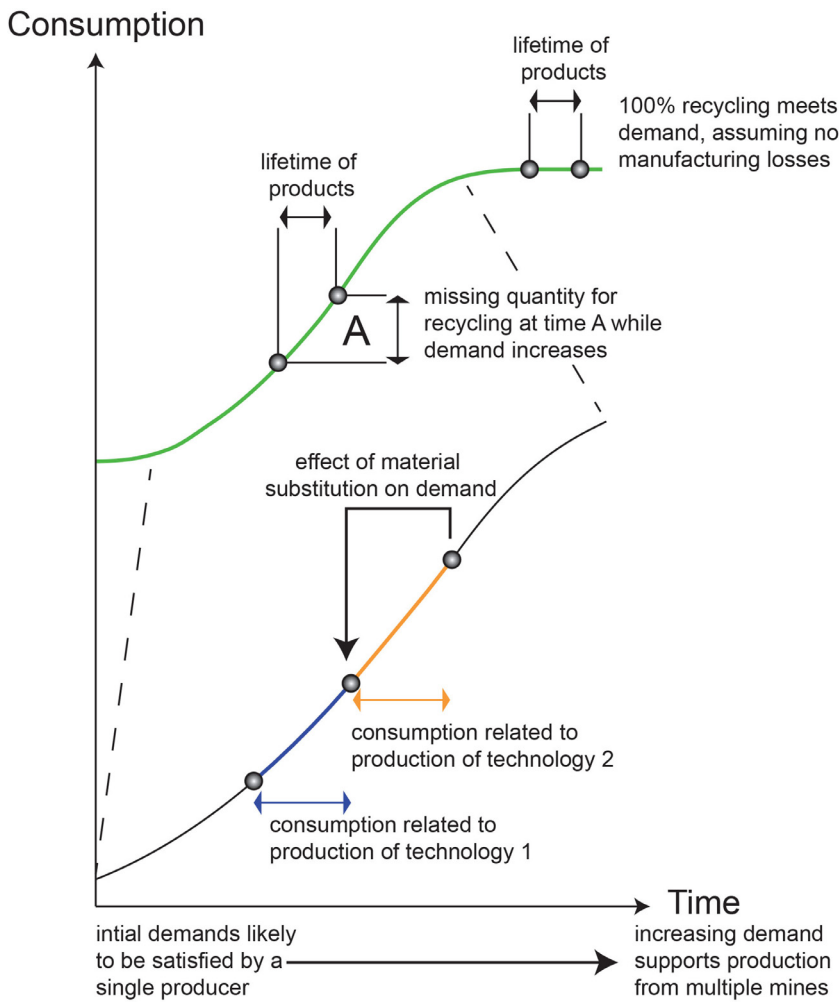


Fig. 1. Idealised growth curve (after Steinbach and Wellmer, 2010), illustrating the limitations of recycling and material substitution to reduce criticality of raw material supply. Growing consumption at time A means that the secondary material available at a later date cannot meet demand. During times of constant consumption, the amount of secondary material available at the end of a product lifetime is equivalent to that at the start of lifetime of the product. This theoretical equivalence supposes 100% manufacturing efficiency and 100% recycling rate. The contribution of recycling to overall consumption is therefore limited by the demand growth rate and the lifetime of technological products. The lower curve shows the potential effect of successful material substitution in one technology (2) on the overall demand for a commodity. Reduced demand can be supplied by a more limited number of suppliers or mines and increase the risks to supply in the case of disruptions in the supply region. This could increase the risk of supply problems for remaining technologies (1).

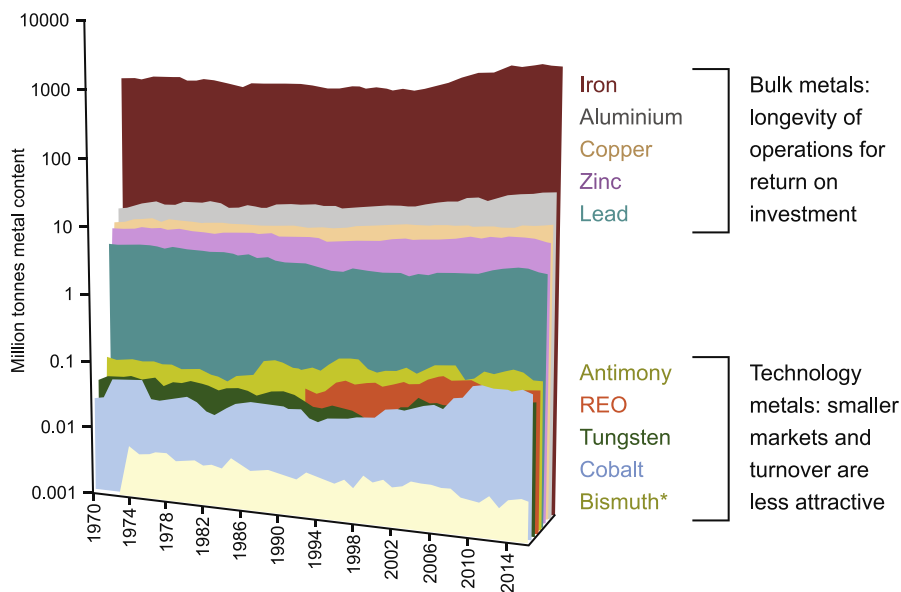


Fig. 2. Global production, in terms of million tonnes of metal content, between 1970 and 2015. Data is from the World Mineral Statistics dataset, provided and maintained by the British Geological Survey. (*Data includes primary and by-product production.).

lower quantities (e.g. antimony) far more significantly than the bulk metals that are produced in the largest quantities.

The manufacturing chain from feedstock supply, to intermediate product manufacturing, and to end-product manufacturing, embodies an incremental increase in value as materials are traded many times (Korinek, 2019) and requires that feedstocks are relatively inexpensive. While the manufacturers and raw materials producers are inextricably linked by supply and demand, the impact of price fluctuations on business is proportionally greater for raw materials producers than for manufacturers, since it relates to a larger proportion of their overall micro-economic model. The production of large quantities of bulk metals at low cost relative to the rest of the value chain, requires that world-class mines run at high efficiency using economies of scale (Humphreys, 2013). The need to maximise throughput (tonnes/hour or tph) from large mines (both super pits and block caves) has driven past innovations in mining practice to reduce operating costs (€/h) with resulting low specific production costs (€/t Run of Mine or ROM). A decreasing cost per unit output with increased mine size favours the development of giant or 'world-class' deposits (Laznicka, 1999) with proven reserves that ensure an extended life of mine and an adequate return on investment. It frequently takes decades from initial discovery of an ore deposit through evidencing success to investors and to full-scale production (Rademeyer et al., 2020). To prove the economic viability of a deposit is a complex, expensive and protracted process, requiring adherence to reporting standards that recognise the interplay of geology, viable processing methods, and issues of access and supply infrastructures (energy, water, etc.). It is another protracted process to gain licencing in a favourable economic, legislative and societal climate. The overall scale of mining operations and the established reporting and finance system mean that the raw materials sector does respond to demand, albeit slowly, for the bulk metals required for infrastructural development and transport.

We consider how the reporting and finance systems that were designed for large-scale mining for bulk metals are applied to metals that are produced in smaller quantities (Fig. 2), including the metals described as critical. We adopt a definition of Critical Metals as follows. 1, they are the wide range of metals with specialist chemical and physical properties that are used in small quantities in the manufacture of low-carbon and emerging modern technologies. 2, they are the metals that are produced by a small number of countries, frequently with political and social infrastructures that create a substantial supply risk (EC, 2017;2014; Moss et al., 2011). We do not focus on those Critical Raw Materials that are biotic or produced as by-products at refineries. Where smaller demand can be accommodated at just a few mines globally, the rate of response of supply to demand has potentially greater impact on the value chain. There is the potential to mitigate supply shortages by substituting alternative materials. But the specialist properties of technology metals mean that some substitutions may result in the end product losing functionality. Furthermore, a decrease in demand for a metal that is already produced in relatively small quantities (Fig. 1) has the potential to create a feedback loop of increasing business risk amongst the producers of raw materials and increasing supply risk for the end-users in the value chain.

The underlying concepts behind this work are the significant contribution of historical contextualisation to scientific interpretation, and the use of historical and contemporary narratives as data in scientific methodologies or modelling to develop innovative paradigms (Büthe, 2002; Cleland, 2001; Mayr, 2000). The work is the culmination of five years of stakeholder engagement and public participation activities across a wide-range of sectors and groups, including resource extraction and minerals processing, engineering and manufacturing, social sciences and ethics, and post-mining communities. Based on this evidence, we discuss the trends that are likely to influence future demand and production – from industrial, economic, geo-historical and environmental standpoints – and examine whether the current paradigm of mining world-class deposits is appropriate for the extraction of

critical and technology metals. We consider whether economies of scale can or should ethically be applied in the context of an abbreviated life of mine in small deposits. We further ask whether a change in the pattern of mining to suit the extraction of technology metals from small deposits is a new innovation, or whether it is an evolution of an ancient and established history of mining that embodies innovation and adaptation. We support our enquiry using case studies as an exploratory tool, with the intention of informing the development of subsequent research methodologies (Rowley, 2000; Yin, 2014). We retain the use of the term 'small deposit' mining throughout the manuscript as far as possible and retain the use of the term 'scale' to emphasise the spatial and environmental footprint of mining operations, to negate challenges arising in the dialogues around artisanal mining contexts as addressed by Sidorenko et al., (2020). We note that small-scale mining is suitable for, but not limited to, mining of small deposits.

2. Criticality And the value chain

Supply security assessments have been successful at identifying which minerals are most exposed to supply constraints in the near future (EC, 2017, 2014; Glöser et al., 2015; Nassar et al., 2020). However, these studies have also been subject to criticism, as different authors have questioned their ability to translate their findings into the development and application of tangible strategies to ensure a secure mineral supply within the context of the value chain. As early as 2011, Buijs and Sievers (2011) stated that assessments "*lack predictive power beyond the short term; tend to overstate the economic impact of a possible supply disruption of 'critical' minerals; fail to distinguish between short-term and long-term problems; fail to take into account the diversity and particular characteristics of the resource markets analysed; and focus exclusively on risks related to the mining and export of raw materials, but disregard the larger production chain (e.g. refining, transport, and trade in semi-products)*". Since that time, a great deal of research has created a deeper understanding of the issues surrounding material criticality, as a function of commodity trading in international value chains. Renner and Wellmer (2019) explain that metals are traded in a buyer's market, where the buyer is able to apply pressure to lower prices in an over-supplied market. This particularly applies to major metals. Amongst the minor metals are the critical metals, defined using criteria that include geographical supply concentration. Analysis by Renner and Wellmer (2019) suggests that this causes supply shocks and price volatility only in a context of regional or national conflict. The authors contend that the reaction to perceived supply shocks on the demand side, or hype, has a far greater impact on price volatility than supply concentration. Frenzel et al., (2017) concur that, due to flaws in criticality assessments, many of the raw materials generally identified as critical are probably not critical. But they state that the issue of supply security remains significant for some sectors, and surveys of criticality continue to identify the materials that are at greatest risk of supply shortage (Hayes and McCullough, 2018; Nassar et al., 2020). Exceptionally, the Covid-19 pandemic has also created enormous short-term uncertainty. Unusually, falling demand for mined products (as economic activity slows down) now coincides with supply-side upheaval (Steen, 2020). Increased risks of supply shocks may ensue. While price volatility is greater for minor metals than for major metals (Renner and Wellmer, 2019), the European Commission emphasises that '*all raw materials, even when not critical, are important for the EU economy*' (EC, 2014).

The European Commission has formulated responses that straddle the value chain and promote more research to optimize supply, recycle materials and to substitute metals in manufacturing processes in a circular economy (EC, 2018). The aim of the circular economy being to maintain the value of products, materials and resources in the economy for as long as possible, to minimize the generation of waste (EC, 2015) and to reduce future consumption (Oberle et al., 2019). Fig. 3 depicts the 27 materials that are currently classified as critical by the European

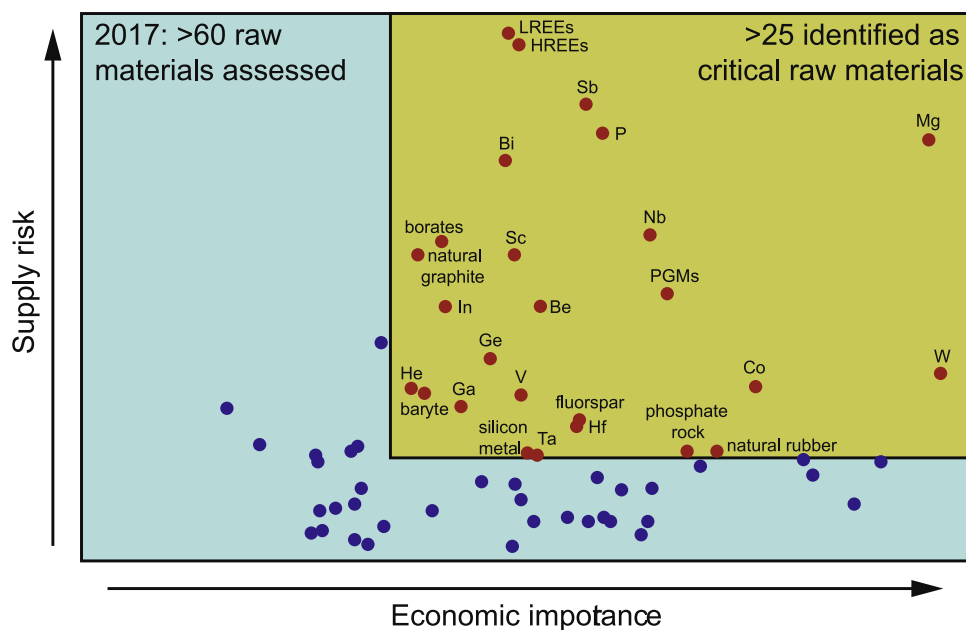


Fig. 3. Critical raw materials (red dots) are important to the European economy, in terms of end-use application and the value added to corresponding EU manufacturing sectors, and at risk of supply disruption from either global producers or suppliers to the EU, considering their governance performance and trade aspects. The risk-reducing measures of substitution and recycled are considered (EC, 2017).

Commission in terms of economic importance and supply risk (EC, 2017). In a background report to the European Commission, Mathieux et al., (2017) examined the sector-specific importance of the critical raw materials, which were linked to all supply chain stages across eight industrial sectors including the automotive and renewable energy sectors. The energy transition required to satisfy climate policies with net zero emissions is inextricably linked to critical metal and semi-metal production (Bazilian, 2018; Frenzel et al., 2017; Giurco et al., 2010; Tokimatsu et al., 2017) by the specific properties required for functionality in technological devices and renewable energy infrastructure. The need for technology metals, whether critical or with little risk of disruption to supply, at the global energy-mineral nexus is concomitant with bulk metal production due to the total materials requirements of energy infrastructure (e.g. Martinez et al., 2009). The potential for supply - demand imbalances during and following the Covid-19 pandemic will increase if the energy industry (Watts and Ambrose, 2020) accelerates its transition to a low-carbon economy. The energy transition, and indeed the current level of technological innovation, require a greater diversity of materials than at any time previously. Critical raw materials are geologically available (Graedel et al., 2014) but any long-term forecast is due to enormous uncertainty in terms of trade relations and emerging economies, technological innovation or environmental limits (Buchholz et al., 2019; Humphreys, 2019a, 2019b).

There is a pressing need for new perspectives to facilitate a transition from the top-level identification of supply risks, and compilation of critical material lists, towards the development of tangible strategies to ensure secure mining-based supplies. Evidence gathered from 29 meetings with stakeholders (January 2014) at the outset of cross-sector dialogue suggested that the business threats of material criticality in the value chain are associated with the speed at which the supply chain can respond to demand or supply shocks. Managing these threats depends on: understanding the source of capacity risks affecting supply and demand; the likelihood of capacity risks developing into disruption events; and the possibilities for increasing the readiness of new capacity throughout the supply chain. Supply-demand imbalances, usually manifested as price volatility in the mineral commodities markets (Buchholz et al., 2019; Renner and Wellmer, 2019), result as a combination of capacity risks and disruption events. When this occurs, the different stakeholders along the chain react according to their own interests and capabilities (capacity readiness). Responses in the raw

materials sector that contribute to capacity readiness are usually prioritised according to criteria such as: investment risks and economic certainty/motivation; existing technological readiness; geological knowledge and understanding of potential new deposits; research and development capacity; and health and safety regulations. These variables determine the amount of time required to restore the balance in the supply chain. For example, new and alternative types of ore deposits may take decades to develop, from initial exploration to the design of appropriate extraction and processing techniques, and subsequently to mine development and production (Rademeyer et al., 2020). Long-term access to raw materials is ensured but real or perceived (Renner and Wellmer, 2019) short-term business risk is not mitigated. The stakeholder dialogues highlighted that the potential solutions are commodity-specific, and considered metal and semi-metal production in two groupings: the commodities that can be produced as by-products of other main metals and the commodities that can be produced as the primary output of mines. The workshop stakeholders considered that addition of new by-product streams to operating mines is a potential short-term solution, but that the addition of new processes in metallurgical flowsheets can prove costly in terms of reagents and energy consumption. Renner and Wellmer (2019) assert that, where by-product extraction methods are in place, producers may react quickly to market signals by increasing by-product recovery from the main mineral when prices increase. If the stockmarket price is insufficient to make processing economically viable, potential by-products are either stockpiled or discarded as waste, with the potential for future extraction (EC, 2015). For commodities produced by mining, small-deposit mining is a potential alternative and short-term solution, where deposits are proven and can be licenced rapidly, but will potentially fail to provide a return on investment. Following the stakeholder dialogues, mining of small deposits was scrutinised in greater detail.

Global mass flow analysis of tungsten, as a case study in critical raw material production and consumption, shows that diverse end-use applications have not induced a geographically diverse raw materials supply (Leal-ayala et al., 2015). This suggests that the climate of long-term uncertainty and short-term supply-demand imbalances described above must also be inextricably linked with external forces. Inequalities in the demand-supply relationships are ultimately created by macro-economics, international trade, foreign policy and the impact of social change on technological innovation. The 'Limits to Growth' report (Meadows et al., 1972) predicted the end-member scenarios that either

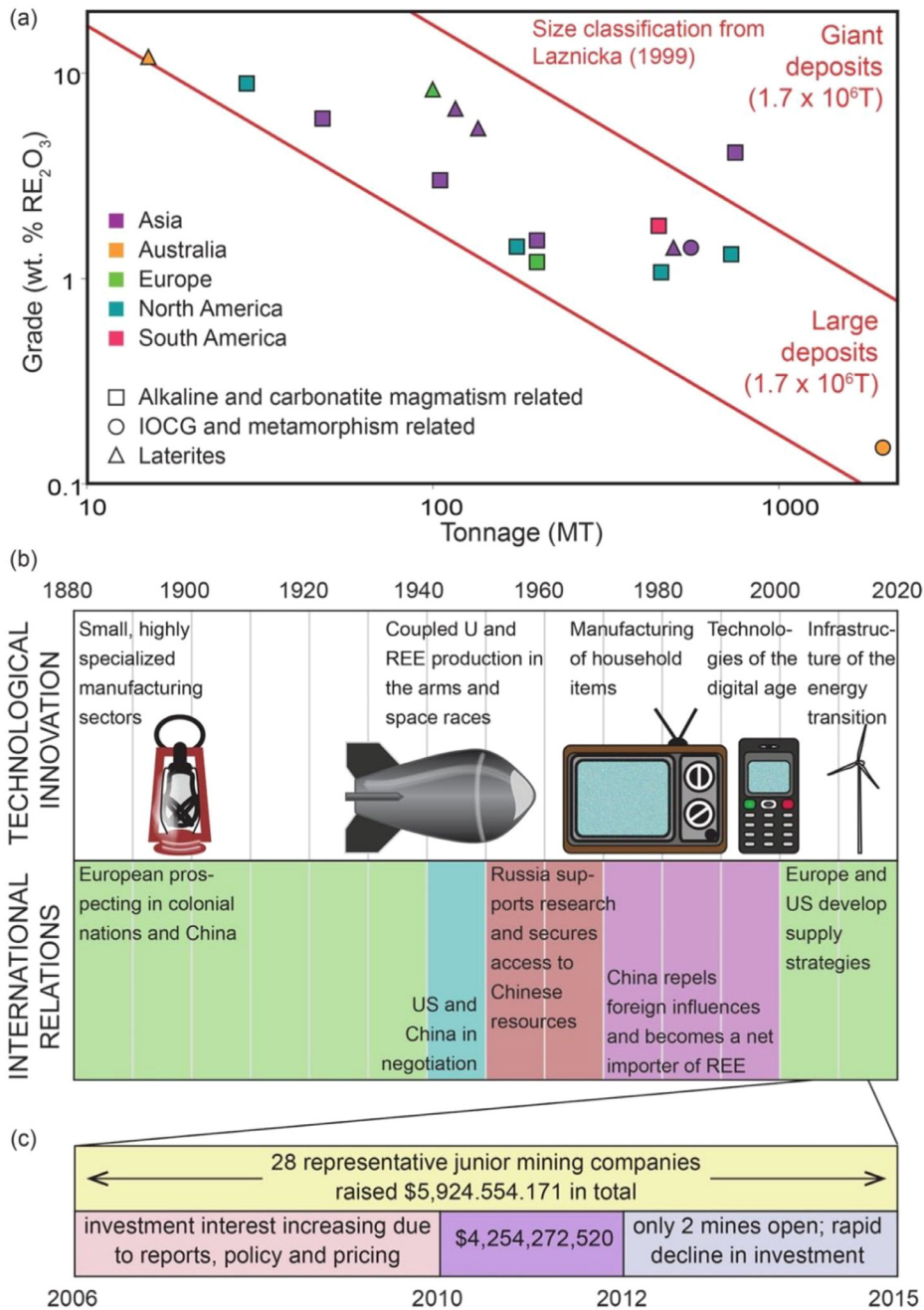


Fig. 4. The geography of REE deposits and production. (a) Graph of size of REE deposits, in terms of tonnage and grade, as a function of location (by continent) and simplified geological source characteristics. Only large and giant ore deposits are shown. (b) Interconnection between technological application of REE and international strategy regarding access to resources. (c) The effects of supply disruption on interest in investment in raw materials during the REE crisis of 2010–2012. (Data and information from Cox and Kynicky, 2018; Klingler, 2015; Smith et al., 2016).

population and industrial capacity would suffer a sudden and uncontrolled decline, or that growth trends would be altered to promote a sustainable ecological and environmental future. While the limits to production of non-renewable, non-fossil fuel mineral resources have not reached peak production (Oberle et al., 2019) and the global economy remains dependant on sustained industrial growth, there is a growing body of evidence that the environmental limits of industrial development have been exceeded (Allwood, 2018; Barnosky et al., 2011; Lenton et al., 2016). (Allwood, 2018) highlights that ‘*techno-optimism*’ for future innovation will not provide solutions to environmentally-limited resource production and consumption across the value chain. The United Nations Environmental Panel consider that mitigation of the environmental impacts of industrialization, including mineral resource

production, in a short time-frame is possible using existing or feasible technologies (Oberle et al., 2019).

Acemoglu et al., (2012) describe the current trend as a hybrid model of directed technical growth and innovation with environmental constraints, which conforms to neither of the end-member models of uncontrolled decline or sustainable futures. Their growth model describes exhaustible inputs as ‘*dirty*’ inputs and they suggest that sustainability can be created by the use of taxes and subsidies to redirect innovation towards ‘*clean*’ inputs. The rhetoric of dirty and clean inputs unintentionally reflects the disconnection between production and consumption in the wider consciousness. For example, perceptions of the negative impacts of *dirty* mining (Harvey, 2014) by consumers are not linked to the provision of *clean* energy with low-carbon emissions, even

though they are inextricably linked by the resources required to build renewable energy infrastructures. It illustrates the need for greater communication of the environmental and ethical frameworks within which the mining industry has variably operated (Sidorenko et al., 2020), and which have been recognised from a humanist perspective in literature since Agricola's *De re metallica* (Hannaway, 1992). The external forces influencing the interconnected critical metal-based value chain and technological development are embodied in social acceptance of mining. It can be argued that social acceptance is inextricably entangled with the historical and environmental identity of mining to a greater extent than it is with the provision of materials to the energy transition for improved societal and ecological benefit.

3. The Geography of critical metal deposits

The onset of mine production at a new 'world-class' mine impacts the global mining industry in a historically-established pattern. Where the economies of scale are applied in a context with low labour costs and permissive regulatory structures, the market is flooded with low cost raw materials. Competitors that operate at a higher cost are ultimately forced out of the market. A classic historic example is the establishment of multiple large tin mines in Asia and South America, in the latter half of the 20th century. It led to the cessation of tin (and tungsten) mining in England's southwest metallogenic province and elsewhere in Europe even though mines were not exhausted. Exceptions to this general pattern have arisen when trade networks have been restricted by external influences, for example when military maritime blockades impeded access to raw materials with lower production costs during the world wars of the 20th century. Tungsten was strategically important to the UK war effort (for armaments and tanks) and tungsten was produced in SW England during both world wars, even though mines were small and production was more expensive than from world-class mines. The success of international trade and the lower cost of international supplies in peacetime made the UK deposits sub-economic, when tin and tungsten were shipped globally using the maritime trade routes established largely as a function of imperial domination (Dalby, 2008). Tungsten is once more of increasing strategic importance, because: 1, it is used in an increased number of modern technologies (Leal-ayala et al., 2015); 2, it has been subject to supply concentration with > 70% (since 1994) and > 80% (consistently since 2010) of metal content produced in China (World Mineral Production Statistics, BGS); and demand has been rapidly increasing in the 21st century (Fig. 2). The Drakelands mine in SW England, which formerly operated as the Hemerdon mine during and post-war, recently reopened as a modern mine after decades of interest to prove a 'world-class' reserve and obtain appropriate permissions to operate. It operated for a very brief period, despite extracting ore from the fourth largest tungsten deposit in the world, because processing challenges lowered production levels. The location of world-class mines therefore varies as a function of the non-renewable nature of ore deposits, an enhanced understanding of the extent of orebodies and their potential for processing, and due to the geographies of international trade and transport.

Geology controls the location and distribution of critical metal, and other ore, deposits but economic, legislative and social factors control which deposits are mined. The rare earth elements (REE) are the most often cited and well-studied example of critical raw materials that have been subject to recent supply disruption. The REE are up to two orders of magnitude more rare in the continental crust than copper (Chakmouradian and Wall, 2012) but they are concentrated in large magmatic, hydrothermal and sedimentary ore deposits (Elliott et al., 2018; Smith et al., 2016). Ore deposits are located on all continents including Europe (Goodenough et al., 2016) but only the Bayan Obo REE deposit classifies as a giant ore deposit (Fig. 4a). Its production statistics, combined with those of smaller deposits including ion adsorption clays, show that China contributed less than 40% of global REO supply prior to 1992. This increased to greater than 90% in 1998

and peaked at 98% of global REO production in 2009. The reasons for the dominance of the Chinese REE raw materials sector in the global market are largely the result of industrial and foreign policy that mark the culmination of a long history of adverse international relations. Klinger (2015) traced the historical and political geography of REE production from 1880 to 1960, as a function of technological innovation, foreign policy arising from military-industrial necessity and the environmental hazards associated with production (Fig. 4b). The Scandinavian placer deposits that supplied the first REE markets in the 1880s were quickly consumed. European nations initially looked to their colonies for alternative resources and the German Foreign Ministry prospected in China through to the 1920s and 1930s. Subsequently, Britain and America developed a 'joint effort to seek out and gain control over as much of the world's uranium and thorium [also REE] deposits as possible' in order to secure and dominate atomic arms developments (Klinger, 2015). Negotiations between the USA and China to collaborate on geological exploration never reached fruition due to the communist revolution of 1949, following which the Soviet Union and China collaboratively developed REE alloys for the space and arms races. The 1970s marked the transition between the atomic and digital ages, when the significance of REE moved from small highly specialized sectors to large-scale manufacturing of the technological hardware of modern life. China had repelled invasive policies from foreign powers and become technologically superior in the rare earths sector, importing separated and refined rare earths, and dominating higher value intermediate product manufacturing (Shen et al., 2019), specifically of permanent magnets.

The established hierarchy of the capitalist world system in the 20th century arose historically from imperial geopolitics (Dalby, 2008), backed by extra-regional maritime dominance of key trade routes (Brewster, 2017). However, 1951 marked the establishment of the Baotou Iron and Steel complex as the industrial heartland of China and the region from which the REE were produced. It is inextricably linked with the evolution of China from an agrarian society into a landlocked economic driver of industry (Cáceres and Ear, 2012). Recent signs of economic stagnation in China due to overproduction and decreasing returns to capital have incentivised the Chinese State to reconfigure its geographic vision in order to continue its policy of economic expansion (Zhang, 2017). Strategies designed to secure resources and business objectives have significantly included the 'Go Global' strategy launched in 1999 and the 'One Belt One Road' initiative announced in 2013. The latter is premised on the resurrection of the Silk Road and the regional maritime security of the Ming Dynasty (Brewster, 2017; Yoshihara and Holmes, 2008; Zhang, 2017). The development of overland trade routes has implications for the location of mining activity, particularly for high value metals produced in small quantities. China has for several decades been a significant producer of multiple metals that are now defined as critical raw materials (for example, tungsten and REE), and is extending its reach to import raw materials from international mining operations, particularly in Asia, Africa and Europe. China's global resources acquisition raises geopolitical issues (Cáceres and Ear, 2012). But it also constitutes opportunities in regions with new models of political, economic and international development (Palit, 2017; Power and Mohan, 2010), initially based on raw materials production with low labour costs. While international trade by multi-national enterprises in China may seem to follow similar imperialistic, state-sponsored patterns of development to European nations during the Industrial Revolution, there are unique aspects (Peng, 2012) that suggest care should be exercised before drawing parallels. The current shifts in the geography of trade and raw materials supply can therefore be framed as regionally-led change, rather than a revolutionary shift (Schouenborg, 2012) in the geopolitical model.

Klinger (2015) asserts that the pursuit of mining opportunities beyond national borders is an effort to outsource environmental degradation, as well as a strategy to preserve domestic reserves. This implies that there is a tension between securing access to critical raw

materials and isolating the hazards generated by mining activities. The REE are used as an example, in that their geological occurrence is often coupled to that of the radioactive elements, particularly thorium and uranium. Large amounts of REEs have been released to the environment in the Baotou Province and other mining areas in China, with harmful effects on local residents as well as the environment (Liang et al., 2014). Environmental protest has grown, influencing national politics as a result (Steinhardt and Wu, 2015). Klinger (2015) describes power as the ability to 'subject some and exempt others from the toxic and radioactive by-products of mining and processing', which suggests that environmental disregard is an aggressive action towards other nations. Some mining companies do not adhere to international norms for best practice in responsible mining, which has the potential to create conflict in mining regions, and potentially negative consequences for China's own economic interests (Li, 2007). An increasing body of literature demonstrates that best practice in responsible mining (for any commodity) relating to environmental protection comes at a financial cost (Humphreys, 2019b, 2000; Soderholm, 2000). Thus, environmental negligence can contribute to price undercutting on global markets. Foreign-owned extractive companies must adhere to national standards of environmental protection, the extent of which is linked to government services and responsibilities (McHenry et al., 2017). Poorer nations may also have expectations of economic development based on the extractive industries, fuelled by the interplay between resource endowments and political manoeuvring (McElroy, 2015; Robinson et al., 2006). In combination, these factors can result in incentives to encourage foreign investment in operations that do not adhere to international norms for best mining practice. Thus, the outsourcing of environmental degradation is tied into economic development, as well as constituting an abuse of power. Developed economies have replaced raw materials production with business sectors further along the value chain, and international business operations have been established in efforts to maintain the low cost of raw materials relative to the value chain.

The Covid-19 Pandemic has thrown into sharp relief the relationships between national politics, international trade relations and the value chain of critical raw materials. China introduced early mitigation measures in response to the pandemic, which caused a significant reduction in demand in a large consumer market. The reduction in purchase of US imports undermined the US-China trade deal (Lee, 2020). Economic responses considered by the US included export controls, investment curbs and 'crackdowns on integrated supply chains' (Politi et al., 2020). The EU and China intended to conclude an investment deal in 2020 (Valero, 2020), but this is now uncertain while the duration and/or extent of economic recession is unknown and while political relations between China and some member states are strained (Rudd, cited by Ging, 2020). The dependence of European manufacturing on raw materials imports from China has influenced EU strategy to develop European strategic and critical raw materials production (EC, 2017, 2014). Steen (2020) contemplates whether the established trend for direct investment in mining and processing by end-product manufacturers may accelerate. If supply chains become increasingly integrated outside of China, this could once more shift the geographical patterns of raw materials production. It could potentially improve traceability of responsibly-sourced raw materials (Young and Dias, 2012), but negatively impact resource-dependant economies (Zhuwarara, 2020).

4. Small Deposit mining and capital infrastructure

Small narrow-vein or complex ore bodies are recognised as having potential for alternative raw materials production capacity (SIP, 2013). They further provide excellent potential for rapid switch-on production, particularly in response to short-term changes in market forces. However, what constitutes a 'small deposit' is not straightforwardly defined. It cannot be defined in absolute dimensions because the metal content

is a function of grade and tonnage, and because the cut-off grade (of what can be economically extracted) is influenced by the market price of a commodity. For example, Fig. 4a demonstrates that REE deposits may be considered large if they have orders of magnitude of between 10 MT ore at > 10 wt% RE₂O₃ or 1000 MT ore at > 0.1 wt% RE₂O₃. Alternatively, Cassard et al., (2015) based the size of deposits on their commodity content, which derives directly from grade and ore tonnage. In order to understand how small a deposit can be and remain viable to mine due to the economies of scale, the notion of 'high-grade' was prioritized. The idea of high-grade is often linked to 'small-scale', and to a certain point, complexity. Consultation within the Bureau de Recherches Géologiques et Minières (BRGM) was used to establish boundaries within which to discuss the notion of small, high-grade (and sometimes complex) ore deposits for a small subset of critical and other raw materials. The cut-off grades used for initial investigations of small deposits were 1% for antimony (metal); 20% of chromium as Cr₂O₃; 0.1% of cobalt (metal); 3 g/t of gold; 5% of zinc or 10% lead-zinc combined (metal). The BRGM established that a total of 201 known mineral occurrences in the European Union satisfied the end-member scenario of high grade and low tonnage alone, with no further determination of economic viability. By establishing the criteria for definition of a small deposit, the framework was created for improvements to the EU-Minerals Knowledge Data Platform. The community of end-users may now identify and locate small, high-grade complex deposits through selection functionalities in a dedicated data layer of documented mineral occurrences. The results have highlighted mineral deposits for further investigation but have also demonstrated the significance of considering the critical raw materials alongside other raw materials. The case study of zinc is interesting since it is a bulk metal that has been extracted in recent decades by large-scale industrial mining using economies of scale, but the large Lisheen mine in Ireland closed in 2016. This has driven up the price of zinc and increased interest in smaller deposits, which were formerly considered sub-economic but may be economic in a higher value commodity scenario. It confirms that methods to ensure rapid response to demand for critical raw materials by small-deposit mining could be applied to commodities other than critical raw materials. The potential for small-deposit mining for any commodity is premised on the notion that it can compete economically with production from mines in larger deposits. This requires critical examination of the financial frameworks within which mining operates.

Industry standard codes, such as the Australian JORC¹ and Canadian NI² codes of mineral reporting, were developed in the late 20th century to combat geological misreporting and subsequent losses on public bourses. They codify best practice methodologies to prevent both fraudulent and negligent misreporting of geological (and thus economic) potential. Understandably these codes became the *de-facto* measurement by which investors fund projects and banks provide project finance³ for the high capital expenditure (CAPEX) and high constant operating expenditure (OPEX) associated with large-scale mining with low price elasticity (Buchholz et al., 2019). Throughout the mining boom at the start of the 21st century adherence to these codes, as well as the many additional responsibilities required by initiatives such as the IFC's Equator Principles,⁴ became an absolute requirement for public companies. The unintentional consequence of these extensive

¹ JORC – The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves.

² NI 43-101 – The National Instrument for the Standards of Disclosure for Mineral Projects within Canada.

³ Project Finance – The long term financing of infrastructure and industrial projects based upon the projected cash-flows of the project rather than the balance sheets of its sponsors.

⁴ Equator Principles - The International Finance Corporation's risk management framework, adopted by financial institutions for determining, assessing and managing environmental and social risks in projects.

reporting codes was an exploration model where risk was held, not in identifying an ore body, but rather finding one *big* enough to generate the investor excitement required to fund compliance with the reporting codes. Driven by the funding requirements of the mining stock markets (particularly the Venture Exchanges⁵ in Canada, Australia and the United Kingdom), the junior exploration companies were required, on the whole, to identify ‘world class deposits’ at vast expense, in order to realise the financial returns promised in their funding manifestos. The capital required to fund the world-class mining operations resulted in long payback periods and left the industry exposed to large financial risk, much of which was written off leaving almost no investor desire to fund exploration. This is classically demonstrated for the critical metals during the REE crisis of 2010–2012 (Cox and Kynicky, 2018). Investment interest in the REE junior companies (Fig. 4c) was precipitated by Chinese rare earth policies and World Trade Organization decisions, media and government announcements, the initial public offering of Molycorp Inc., rare earth element prices, and junior mining company stock prices (Cox and Kynicky, 2018). REE prices peaked in 2011 and, over two years, \$4.2 billion was invested in 28 junior companies (Fig. 4c), only two of which had the largest share and went on to produce REE for the general market but not at great or lasting profit. The investment community lost much of its interest in the REE by 2015 for multiple reasons, including the identification of new resources that reduced the perceived risk of China's dominance (Cox and Kynicky, 2018) and the lack of an adequate return.

It has become increasingly unrealistic for small- and medium-sized mining companies to rely on traditional debt-equity financing to open new projects following the global economic crisis (2008) and the more recent commodities crash. Capital investment is now often sourced from internal cash-flow and this phenomenon is forcing a change in the way miners evaluate projects. The historically accepted norm of high capital cost (>USD\$100 Million), high fidelity orebody definition and the associated feasibility studies, is no longer fit for purpose in the emerging commodity market. Large, expensive resource drilling campaigns and studies, required to achieve regulatory code compliance, place a ‘capital threshold’ to access public market funding which is prohibitive to all but the largest of mining companies. Hundreds of junior companies have de-listed and many lesser tonnage deposits were discounted as unfeasible even if they were closer to the end-user market or located in more stable mining jurisdictions. This constrains the production market and increases the real or perceived supply risk of critical raw materials. The longer the current model continues to be used, the higher the risk to global resource security; with little new exploration, depleting reserves and increased market fragility. Small to mid-tier miners and mine developers are now increasingly looking for a different development funding model based on the potential to quickly establish the *minimum* economic ore reserves required to commit to start a small-scale mining and processing operation.

The new reality is that exploration needs to identify, in the first instance, the *minimum* economically viable ore deposit required to justify start-up. Industry needs a model where, for the minimum capital expenditure, cash can be generated to fund further exploration or to simply mine out a small ore body. If sufficient deposits are identified (noting that exploration of this kind is more likely to ‘follow’ the mineralization than commit to thousands of metres of core drilling) then the cash generated by the initial operation will be used to upscale the operation or fund further resource definition exploration. In this proposed model, geographically-dislocated small-deposits (of <500,000t for example) could be operated in a managed portfolio (Njike and Kumral, 2019) as a ‘deposit-cluster’, facilitating the regeneration of a whole region. The traditional model for such clusters would be trucking

of mined ore to a central processing plant; this is often neither logistically feasible (due to terrain), economically viable (due to ore grades, distances or prices) or socio-environmentally desirable (due to high-impact traffic). In the future the small, high-grade but often narrow-veined or chemically complex deposits that are present across Europe (and in other regions) must be made viable. Technological mining solutions already exist in principal, which include modular processing equipment that can be deployed without substantial infrastructure development costs and innovative waste disposal solutions, although their application in short-duration mining of small, high-grade and complex deposits needs further consideration.

It is the general case that exploitation of small deposits has been limited since financial institutions are attracted to larger projects offering considerable arrangement fees and the promise of substantial, long-term interest repayments. However, in recent years the mining sector has come to recognise that risk is not entirely proportional to the scale of mining operations. Small deposits are amenable to small-scale mining operations and, in response to market forces, small-scale mining in larger deposits also provides significant opportunities (Quirke et al., 2019). The implication is that small-scale mining may apply to both small deposits and large deposits, as well as to both critical raw materials and bulk metals. The mining industry, operating at all scales (Sidorenko et al., 2020) and for nearly all commodities, is now facing unprecedented challenges due to the Covid-19 pandemic. Due to reduced demand, bulk metal prices fell by 10–15% between 4 March and 2 April 2020 and the price of the critical metals platinum and palladium fell 40% in a comparable time period (Laing, 2020; Ahmed, 2020). The concomitant fall in share prices was comparable to that of the financial crash of 2008–2009 (Laing, 2020). It is likely that multiple mining operations will become sub-economic, particularly where additional capital costs are required to re-open mine sites. Small deposit mining by small-scale operations may become more attractive in a post-pandemic context, due to the lower investment required, in a market of low prices, low production and potential over-supply.

5. Environmental And social narratives as drivers of ethical mining solutions

Extraction from only world-class mines imposes fragility upon both the global market and local economies. Mining operations generally have large socio-economic, sometimes political and environmental impacts, both positive and negative. Over the next 100 years, an intensifying demand for mineral resources and the exploitation of lower commodity grade ores will lead to the doubling of current annual global waste volumes and the disposal of an additional 2000 km³ of solid mine wastes (Lottermoser, 2010). Mining and production of metals causes the dispersion of metals and metalloids (Martínez López et al., 2008) as well as health hazards. The centralisation of large-scale mining activities in few geographical locations concentrates heavy machinery and traffic within a single geographic location and requires vast transport networks that result in a globally high environmental impact. In response, the International Maritime Organization has capped sulphur limits in maritime fuel at 0.5%, effective from 2020 (Terazono and Hume, 2017). Dramatic increases in the cost of shipping are expected (Raval et al., 2019) and, coupled with the energy requirements of crushing vast quantities of low-grade ore, the price of metals from a dominant global supplier is likely to rise. Should the environmental cost of managing wastes and preventing tailings dam failures also be included in the price of commodities (García et al., 2017), then environmental factors increase the economic feasibility of developing local or regional supplies from small, high-grade deposits that are selectively mined for lower waste production per unit cost.

Modern mining operations in the small deposits of historic mining districts will likely encounter the waste of former mining activities. Such legacy wastes were created outside of modern frameworks for responsible mining practice and, depending on the type of ore deposit,

⁵ Venture Exchanges – stock markets established as liquid secondary markets for small and medium sized companies. Examples of which as the ‘TSX’ in Canada and London's AIM market.

can continue to release deleterious elements into the environment. For example, specific waste dumps at former sites of extraction in Italy pose a carcinogenic risk due to the presence of arsenic and a risk to groundwater due to the presence of nickel (Antonella et al., 2020, 2018). The recovery of critical and other raw materials from extractive waste is not a widespread practice, even where it is technologically feasible, economically viable and of environmental benefit (EC, 2019; Mehta et al., 2020; Nevskaya et al., 2020). However, environmental and social licenses to operate may be predicated on the removal of pre-existing contamination, since specific requirements exist for both the minimisation and the recovery of extractive waste (EC, 2015, 2006). Extractive wastes are considerable in mines that remove few commodities, and only above cut-off grades, due to the poor economic returns from additional and costly processing streams. Inclusion of legacy waste treatment in Environmental and Social Governance (ESG) may improve the business case for secondary raw material production as part of the environmental cost of mining (Armstrong et al., 2019b, 2019a; Humphreys, 2019b). Selective mining in small deposits should produce lower waste per unit cost than mining of high volumes of low grade ore at world-class mines. However, the overall return on investment is smaller than for large-scale mining: environmental costs will constitute a larger proportion of unit costs, particularly where mining of small deposits is of short duration and requires that both historical and contemporaneous wastes be managed. The need to include the environmental cost of mining in economic planning is acute for mining of small deposits.

The 'Geoethical Promise' of the International Association for the Promotion of Geoethics places the interest of society foremost and requires the protection of the Earth system. It echoes the European Charter of Fundamental Rights, which states that the principles of good Ethical practice include the primacy of the interest and welfare of the human being. Since the welfare of the individual (whether human or otherwise) is affected by the community and the environment in which it lives, the objectives of a population may vary as environmental circumstances change (Mayr, 2000) and the environmental and social aspects of resource extraction are inextricably intertwined. Sociological ethical considerations in mining were not the driving force behind the emergence of social licencing, which instead originated as an industry response to opposition and a mechanism to ensure the viability of the sector (Owen and Kemp, 2013). There are no international treaties to control comprehensively and effectively the social and environmental impacts of mining and the advancement of responsible mining has therefore rested essentially on national and sub-national regulation and the business sector. At a very general level, social license can be defined as expectations and demands on a business enterprise that have emerged from neighbourhoods, environmental groups, community members, and other elements of the civil society surrounding the enterprise (Raval et al., 2019). It stands to reason that social licensing falls short of the real need to implement ethical considerations in mining because opinions as to what constitutes an ethical approach are influenced by individual value systems and governance factors. Ethical approaches of individuals are a function of education and training, professional codes and relations, and the metrics of the society in which mining is practised (Caldwell, 2006; Lu et al., 2017; Owen and Kemp, 2013; Siegel, 2013). A workshop of stakeholders drawn from the mining industry, NGOs, academia, social practitioners and ethicists examined the question of whether a set of actions devised to gain social acceptance was also a set of actions based on the ethical protection of the rights of the individual, and how this might apply to small deposit mining. The group considered that ethical mining is responsible mining but that it might require a reconsideration of the business model for small deposit mining, as a function of truncated life of mine. The speed at which mining proceeds and the small size of deposit requires the most rigorous environmental protection to mitigate the negative impacts of mine closure. Moreover, the economic benefits of rapid extraction may not be socially practicable, where community gain in

terms of employment and satellite business development are rapidly withdrawn. Small deposit mining may require a new relationship between mining and society.

An argument that ethical mining establishes limits on extraction, once the grade is diminished in large deposits (Priester et al., 2019; Siegel, 2013), is automatically applied to small high-grade deposits since the latter cannot operate on economies of scale. Communities are less likely to become economically over-dependant on mining of small deposits than on long-term mining operations (Tserkezis and Tsakanikas, 2016). Economic benefits based on supply chains (Xing et al., 2017) are unlikely to become well established, or perhaps even to persist following closure of a mine in a small deposit that is not part of a regional cluster of mines. Innovative approaches to Corporate Social Responsibility must therefore be considered. It is unclear as to whether either a smaller mining operation close to a community, or a clear delineation between mining corporations, local communities and governments or policy-makers will confer greater trust (Harvey, 2014; Hill and Lillywhite, 2015). More work needs to be done therefore to bring these disparate groups, with different priorities and agendas, closer together in order to realise the future of mining as environmentally and socially accountable. There is a movement towards establishing the societal and environmental implications of implementing small-scale mining in a European context (Sidorenko et al., 2020) as the underpinning of policy recommendations. But further steps must be taken to facilitate sustainable small deposit mining, perhaps by encouraging a greater number of mining companies to adopt a business model of co-creation with an emphasis on ethical responsibility. This signals a critical shift for the present, while also establishing a lasting economic, environmental and social legacy of mining companies. As just one constituent in mixed and often diverse local and regional economies, small-scale mining operations offer a significant benefit to local communities, not least in building the grounds for economic resilience when mines close. It should be incumbent upon mining companies undertaking small-scale mining to include creation of diverse economic opportunities in their social investment portfolio to mutual economic benefit.

6. Circular Narratives in the history of mining innovation

There remains a great deal to be done to fully realise the range of benefits offered by small-deposit mining regimes in nations where high-CAPEX, large-scale mining dominates. In order to achieve the transition called for here, it is essential that we reveal the ways in which historical and ideological frameworks shape current understandings and representations of mining, and industrial and technological change more widely. In doing so, this section offers an alternative approach to the future of mining in the twenty-first century, by examining the ways in which historical narratives can be usefully employed to inform current attitudes and perceptions.

The significant contribution of History (and humanities more widely) concerns the ways in which we choose to narrate the past, present and future of mining. The large-scale, high-tech, high-investment, high-returns business model is driven by a particular ideological agenda, embedded in a capitalist model of continued progress and growth - the threads of which can be traced back to the eighteenth century in British elite culture (and even further back in Asia). Narratives of industrial revolution construct a progressive account of technological innovation, efficiency and growth. Indeed, as debated by the World Economic Forum, some commentators have suggested that we are currently in the midst of a fourth industrial revolution, which promises a range of benefits to global economies and societies (Humphreys, 2019a; Prisecaru, 2016). In Prisecaru's synopsis the first industrial revolution started with the invention of the steam engine, a technological advance that allowed the transition from feudal to capitalist society. He goes on to summarise that each revolution, including the transition to a post-industrial society today, was related to specific

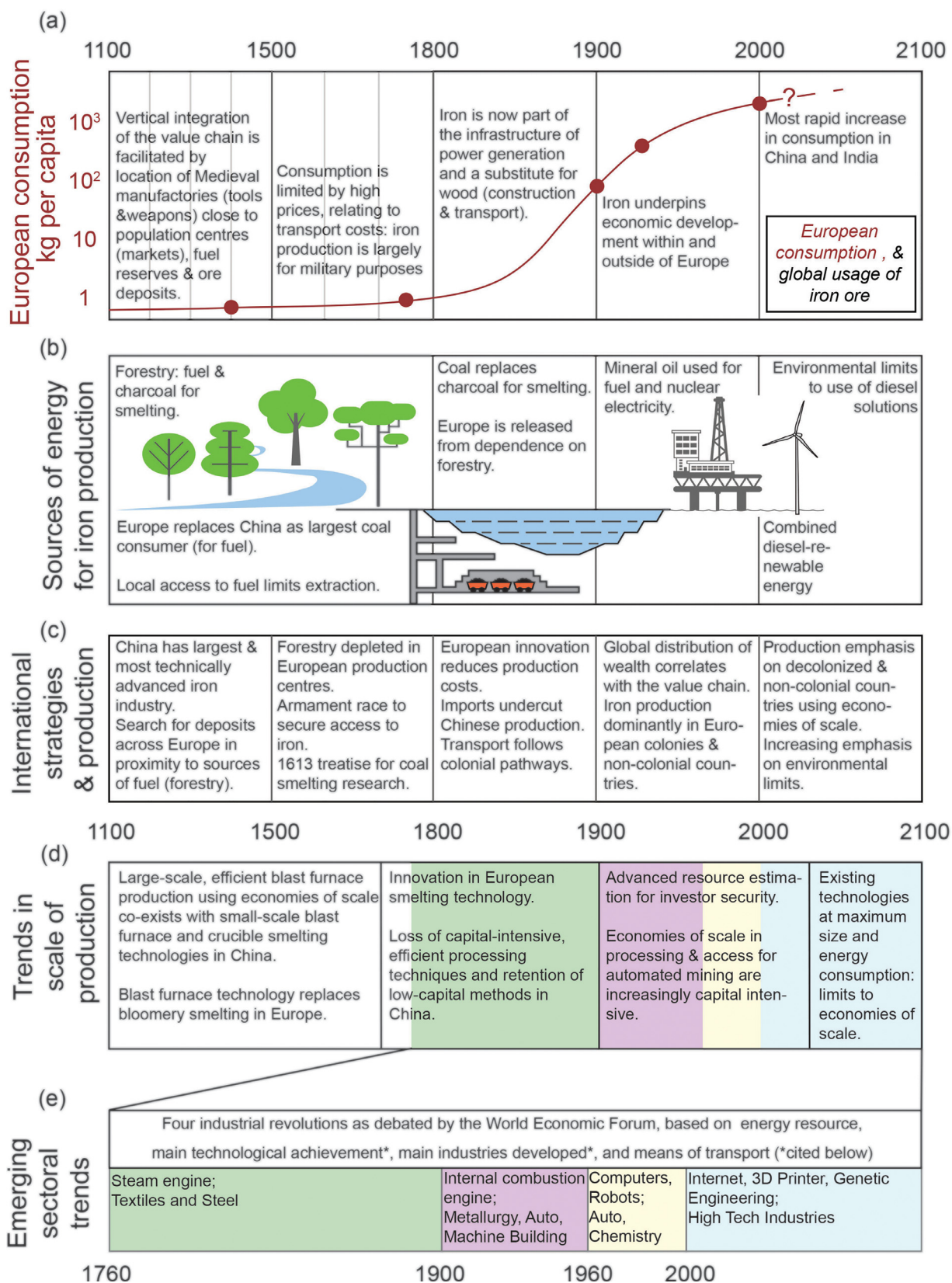


Fig. 5. Trends in production of iron ore from the 12th to 21st century as a function of European consumption (a), source of energy (b), international economic (and political/military) strategies for production (c), the scale of international mining and processing (d), description of industrial revolutions for economic forecasting of sectoral trends (e). Compiled using data from Boserup, 1981; Nakajima et al., 2018; Prisecaru, 2016; Wagner, 1995; the World Mineral Statistics database of the British Geological Survey and online statistics of the United States Geological Survey.

energy resources, and technical innovations that stimulated economic growth in response to humanitarian issues and decreased prosperity (Prisecaru, 2016). Prisecaru adopts a post-humanist philosophy, whereby resource efficiency and technologies release society from physical labour, but he neglects consideration of the value chain as it relates to raw materials.

Fig. 5 demonstrates the interplay between energy resources, investment, innovation and scale of production using iron ore as an example. Iron ore is now produced in greater abundance than any other metallic raw material (Fig. 2), but it was a critical raw material produced in proximity to markets throughout the Middle Ages. Significantly, the concept of vertical integration of the value chain was a theme in Medieval manufactories of Europe and in areas of China up to the 19th century that were isolated from trade routes (Boserup, 1981; Wagner, 1995; Fig. 5a, c, d). Efficient, cost-competitive and capital-intensive production methods that operated using the economies of scale were discontinued in China due to the combined effects of a 19th century national downturn, foreign competition, and alternative investment opportunities (Wagner, 1995). In contrast, skills and low-capital production methods were retained for local production and manufacturing, where technological inefficiency was balanced by low labour costs and the high transport costs of importation. In Europe, the location of mining changed as a function of energy provision (Boserup, 1981) and mining adapted to capitalise on new forms of energy (Fig. 5 a-c). The intertwined relationship between mining for raw materials and energy requirements was as instrumental in driving mining innovation (e.g. water-power, the steam engine, ventilation, smelting), as it is today for renewable energy.

In the context of historical research, the innovations that have been described as ‘revolutionary’ (Prisecaru, 2016) emerged incrementally over time (Fig. 5, d-e), and were often complex, contingent and contested. Historians (e.g. O’Brien, 2017) have been at pains to show that there is no straightforward, linear account of industrial change over time. Placed on a chronological timeline, punctuated by a sequence of historical precedents, the notion of revolution offers an optimistic vision of a future in which technological change is imagined to signal a new, improved and progressive human epoch. Commenting on the late eighteenth and nineteenth century, Jonsson (2012) argues ‘*the unintended consequences of the Industrial Revolution challenge deep-seated assumptions about technology, the environment and economic growth*’. In his words, ‘*historians can no longer treat the environment as merely a pool of resources at the disposal of Promethean technology*’. Commenting on energy and the industrial revolution, historian Tony Wrigley (2013) laments the discourse of abundance and plenty, infinite progress and economic growth achieved through the unchecked exploitation of fossil fuels. Humanity stands at the edge of a precipice, he writes, having arrived at this junction by the consequences of continuing to release carbon into the atmosphere at an exponential rate. The narrative that linear patterns of progress and growth cannot go on into the future is reinforced when we consider the multiplicity of possible environmental tipping points, particularly those that relate to energy fluxes, and the economies of scale in mining (Humphreys, 2019a; Lenton, 2013; Lenton et al., 2016).

In Patrick O’Brien’s (2006) words the industrial revolution was forged through ruthless forces “*conquest, internal colonization, the violent expropriation of ecclesiastical and common land, and the systematic accumulation of power by closed aristocratic elites*”. It is not a term to be used lightly therefore. Calling upon homogenised accounts of any so-called ‘revolution’ as an identifiable and measurable event is further problematized when we consider the international context. Historians have shown the inadequacy of giving precedence to the British model of industrial revolution (as summarized by O’Brien, 2017). Across time and space, change occurred at different times in different places and often as an outcome of very different contexts and circumstances. When examined in global perspective, historians have persuasively argued that there was no one neat model of change; rather the history of

industrial and technological change splinters both geographically and socially. This is mirrored in analyses of global trends and systems in order to identify intervention points. Rather than considering technological innovation as progressive and ‘revolutionary’, Steffen et al., (2015) describe the ‘*Great Acceleration*’ as a growth/collapse economic pattern accompanied by global inequity. The authors postulate that the approaching stabilization of global population and leapfrogging adoption of low impact technologies in the developing world may pave the way to decoupling development from negative environmental impacts. This objective would be accelerated if leapfrogging included adoption of practices to identify and encourage virtuous tipping points in human systems (Lenton, 2013). The implication is that economic and environmental trends are likely to be disrupted by actions in the developing world, which dominates global growth. In these nations, small-scale and/or artisanal mining remains a very significant part of mixed economies (Hilson and McQuilken, 2014), and can form a social and economic practise that safeguards both environments and communities.

Step changes in mining or mining paradigms, as they learn from historical or artisanal mining of small high-grade deposits, should therefore be phrased in the context of circular or entangled narratives, rather than historical assumptions based on linear, revolutionary change and ever-greater technological progress. The alternative circular model takes on board continuities – social, cultural, environmental – as well as identifying moments of change. It takes on board the lessons of history that illustrate the environmental and social degeneration of landscapes and communities in past (and present) mining regions. Continuing to reproduce narrative frameworks of unrelenting progress and technological advances, while overlooking socio-environmental orientated strategies for sustainability and resilience, is clearly open to critical question. As argued here, an understanding of historical processes of change as contingent and non-linear opens up new frameworks for thinking about the present and future development of mining. Rather than viewing the past as redundant, an outmoded yesteryear, the circular and entangled model places micro-level knowledge systems and societal needs and practices originating from within local communities at the foreground of a new mining ethics and sustainable policy. It is only by taking seriously our responsibilities towards individuals and communities, and the environments in which they live and work, that the right decisions can be made in producing future mining solutions with sustainability at their core. By investing in highly specific technological innovations to extract minerals on a small-scale, we can begin to ensure the least amount of damage to local environments, while also supporting resident communities beyond the life-span of the mines. By thinking critically about the ways mainstream history is written from a particular ideological perspective it becomes possible to rethink the present and indeed lasting legacy of mining into the future.

We are not arguing for the uncritical re-generation of historical small-deposit mining practices, but rather that lessons from larger mining operations must be applied in the design of current approaches, taking on board local knowledge and needs. For example, technological innovation in bringing automation to large mines has resulted in the capacity to extract minerals from low-grade ores that would not be cost effective under a manual labour regime. And the three common reasons for the failure of mining operations – overly optimistic mine design and scheduling; resource and reserve estimation that is too local or site specific; and inadequate metallurgical test work and sampling that results in scale-up problems (McCarthy, 2003) – will continue to apply. Yet paradoxically, automation has not resulted in a secure supply of specialist raw materials, and escalation of waste and environmental degradation detract from economic gains. Thus, revolutionary claims that emerging technologies will produce positive outcomes are in danger of bordering on hype (Simakova and Coenen, 2013), unless placed into a sustainable context. If technical challenges can be overcome, rapid start-up and mine closure can then only be achieved responsibly where mining operations are environmentally and socially

acceptable within an agreed ethical framework. A major change in mining trends would include some of the characteristics of conventional, historic and artisanal mining practices combined with innovative modern mining methods with lower infrastructure costs. Taken together, this integrated approach has the potential to alleviate the market fragility of critical raw materials and to reduce the negative socio-environmental per site impacts of mining. Thus, the approach will support the United Nations drive towards partial or total decoupling of economic growth activities from negative impacts on society and environment (Oberle et al., 2019).

7. The Future of mining

The proponents of ‘*revolutionary*’ change employ an established, yet overly simplistic, argument for technological solutions, supplied by abundant raw materials that will drive societal and economic growth. A more sophisticated analysis moves away from simply tracking the pace and scale of technological innovation over time, by exploring instead the entanglements of social and technological relationships across time and space. History sheds light on human interactions, on the extent and limits of cooperation, and a time-deepened understanding of social and environmental entanglements. Moreover, technological developments do not emerge in a vacuum: situated knowledge and practices, and decision-making are based on past antecedents that encompass economic considerations but also a raft of intersecting social, cultural, political, governmental opportunities and constraints. Over the course of the last two hundred or so years, alternative models based on small-scale processes of extraction, increasingly failed to fit the prescribed capitalist agenda. This disconnection constitutes a fundamental issue for the proponents of alternative models of mining, including the mixed economies of artisanal mining communities. It is important therefore to consider rewriting the story of progress and change as one of ethical responsibility, social respectability and environmental care. This requires us to be more discerning about referring to historical models like ‘*industrial revolution*’ and its historical precedents. We are suggesting neither *revolutionary* change nor a return to past modes of mining, but instead to think through the past in order to facilitate the emergence of a sustainable small-deposit mining framework for the future.

The diversity of raw materials required for manufacturing of modern technologies requires a diverse set of mining solutions. Technological innovation for a global low-carbon economy requires raw materials with specialist properties that cannot all be produced securely and sustainably using automated low cost per unit production from world class and giant ore deposits. In addition, Europe is facing the fact that it has been largely mined out of world-class deposits, compared to the “big” mining nations. The authors believe that the future of the mining industry in Europe will be increasingly dominated by small to medium, often privately owned companies, possibly augmented by community-led consortiums. These operators and the projects they champion, will not be of the scale required to attract traditional finance models following the 2008 financial crisis. Going forward both exploration and exploitation will be funded from internal cash-flow, generated by a company’s operating assets. There are very few companies with sufficient surplus cash and strong enough balance sheets to commission the model of high throughput mining and processing plants that a debt financed major (or state-subsidised entity) will look to deploy. Until a low-cost, low-impact, sustainable alternative can be developed, the potential to fully unlock the mineral reserves of Europe and elsewhere will not be realised. Technology will play a huge part in this evolution in mining affairs, but mining code and practices will also need to be revised to fit such small and mobile operations. The traditionally held conviction of scale has to be debunked and many of the recently presumed assumptions about feasibility and geological certainty re-evaluated in order to develop a set of different mining solutions appropriate to the increasing array of raw materials required by modern society.

Governing bodies have recognised the need to accelerate innovation to increase security of supply of raw materials. The European Innovation Partnership (EIP) on Raw Materials identified a Priority Area for research and innovation entitled ‘Technologies for primary and secondary raw materials production’. The description of the Priority Area articulated that technological challenges along the entire raw materials value chain need to be addressed by production solutions that avoid environmental damage and engage society. Specifically the Commission solicited research on the development of new sustainable selective low impact technological solutions for mining of small mineral deposits on the land. Collaborative research is underway, based on the following characteristics of a new mining paradigm:

1. Material criticality can be reduced by increasing the capacity readiness of the supply system. An increase in the rate of response of raw material supply to market forces can be achieved by facilitating access to multiple small deposits in Europe.
2. The extant model of high cost orebody definition and pre-feasibility studies can only be supported by very large mineral deposits. Such deposits are increasingly low grade and require constant technological optimization to remain economic. The current mining paradigm cannot facilitate exploitation of small high-grade deposits. A new mining paradigm is needed.
3. High population densities, sensitive environmental conditions and multiple land uses require that mining produce minimal waste, consume minimal energy and provide maximum benefit to local communities. Mining solutions for small high-grade deposits should therefore include reduced throughput of material by selective mining, mine plans with an appropriate workforce model, and an ethical relationship with community.

Although catalysed by concerns over access to critical raw materials, the re-emergence of small deposit mining is set to become an important part of a diverse raw materials production sector for multiple commodities as prices increase in response to energy demands and transport costs. Historicity demonstrates that the emerging iteration in the circular narrative of mining evolution borrows from ancient and artisanal practices of following high-grade ore materials at minimal cost, but mining is now fundamentally reinvented for environmental and societal best practice. This is particularly important to help resolve economic land-use conflicts and to unlock resources in densely populated or sensitive areas. The relevance of small-deposit mining by small-scale operations to global supply may be heightened as industry emerges from the Covid-19 pandemic. There is uncertainty around the duration and location of supply shocks due to the pandemic, such that existing supply chains may be challenged. There is uncertainty around the duration of reduced demand, potentially creating oversupply. Price volatility ensues in either case, such that mining operating at lower cost (both CAPEX and OPEX) may be an attractive option.

8. Conclusions

The task outlined at the start of the manuscript was to examine the paradigm of small-deposit mining using historical and contemporary narratives, case study and stakeholder perspectives. Mining of small deposits was considered as separate from the concept of small-scale mining (Sidorenko et al., 2020), since the former transects historical and contemporary narratives and the latter has multiple modern contexts. In so doing, we intended that the frameworks and criteria be established that will enable further discourses.

We outlined, in multi-disciplinary framings, the long-term trends of: (i) an increasing and larger resource base that is needed by society; (ii) shifting patterns of resource supply and consumption as a function of multiple global externalities (political, economic and societal); (iii) the environmental limits that are now exceeded by our industrialized society. We considered the impact of short-term criticality due to real or

perceived supply-demand imbalances, including the impacts of conflict or the Covid-19 pandemic. We placed historical perspectives on mining, innovation and industrialisation in the context of sustainable global development and the mineral-energy nexus for the low-carbon economy.

The narratives of past, present and future mining highlight that existing and feasible technologies for selective mining of small-deposits can have smaller and shorter duration impacts (both positive and negative) than large-scale mining of low-grade ores. Thus, the expansion of mining in small deposits will require a new relationship with society, acknowledging that the legacies of historic mining activities influence societal perceptions of modern mining. Opportunities exist to consider mining of small deposits as part of locally-diversified economies and remediated environments, as well as responsive to global volatility in metal markets. Mining of small deposits will require less investment and may offset risk for mining practitioners and investors, but it will require a reinvestigation of current reporting and finance models. International trade relations, foreign policy and the geography of value chains may limit the potential for geographically-dispersed mining of small deposits. However, increasing global demands for best practice, equitable distribution of opportunities and reduction of carbon emissions now coincide with initiatives to support the circular economy as well as potentially greater short-term supply-demand imbalances. In combination, these external forces may create a climate that is amenable to the expansion of mining of small deposits.

We conclude that the wide range of raw materials for modern technologies require a diversified set of mining solutions that can usefully include selective mining of small deposits, if it can be decoupled from the negative impacts of historic mining practices. There is a pressing need for empirical data on the extent of small deposits, to underpin development of the socio-economic frameworks that could facilitate a more diverse portfolio of future mining solutions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Acknowledgments

KM would like to thank all IMP@CT project partners and Stakeholder workshop guests who contributed to the development of concepts presented in this manuscript, discussed ideas or questions, and helped with revisions. This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 730411 (2016–2020). In addition, the stakeholder interviews concerning the value chain were funded by NERC under grant number NE/L001632/1 (2014). AJB publishes with the permission of the Director, British Geological Survey. J. Cilliers is particularly thanked for his contribution at the NERC-funded interviews and during dialogues surrounding response to material criticality. Three anonymous reviewers are thanked for their constructive comments, which have enhanced the manuscript.

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