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Re-thinking complex orebodies: Consequences for the future world supply of copper

R.K. Valenta [a], D. Kemp [b, *], J.R. Owen [b], G.D. Corder [c], É. Lèbre [b]

[a] W.H.Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, St Lucia Campus, QLD, 4072, Australia
[b] Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, St Lucia Campus, QLD, 4072, Australia
[c] Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, The University of Queensland, St Lucia Campus, QLD, 4072, Australia

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ABSTRACT

The supply of copper underpins global economic growth and human development. Forecasts predict a market deficit of 600 kilotones of copper metal by 2021. Accessing new and undeveloped copper orebodies is critical to meeting projected demand. The mining industry has historically addressed supply challenges by capitalising on rising metal prices. We test the assumption that a price rise will 'unlock' previously uneconomic orebodies. It is argued that reacting to a simple price rise is instead likely to 'unleash' an unacceptable suite of environmental and social impacts. This paper examines 308 of the world's largest undeveloped copper orebodies and provides a current, comprehensive, multi-factor risk profile of the world's future copper supply. Our analysis reveals that a significant proportion of future copper supply involves factors that are not immediately price-sensitive, and that a rapid unlocking of these ore bodies could have negative ramifications for economic growth, human development, and the transition to a low carbon future.

1. Introduction: copper's supply challenge

Copper plays a crucial role in modern society. As an essential material in the building and construction, power, and information technology sectors, copper underpins global economic growth and human development (Doebrich, 2009). Transitioning to a low carbon future will depend on the continuing widespread use of copper in renewable energy infrastructure, including solar panels, wind turbines, and electric vehicles (Kleijn et al., 2011; Hertwich et al., 2015; Vidal et al., 2013). In fact, the achievement of many of the United Nations (UN) Sustainable Development Goals (SDGs) (UNGA, 2015) – from good health and well-being to clean water and sanitation – relies on future copper supply.[1]

From the turn of the 20th century, copper production rates have grown in response to increasing consumer demand (Kelly et al., 2017). Due to continuing high levels of demand, forecasts predict a market deficit of 600 kilotones of copper by 2021 (Davidson, 2017). By 2050, the demand for copper is projected to increase 300% above current levels (Elshkaki et al., 2018). While copper is one of the most widely recycled metals, the recycled content in new products is expected to remain below 25% for the foreseeable future (Graedel et al, 2011). Accessing new and undeveloped copper orebodies is therefore critical to meeting projected demand.

The current stock of known, undeveloped copper orebodies is characterised by its complexity. Copper mines of the future will be lower grade, deeper, and larger footprint operations (Prior et al., 2012). These mines will consume more energy (Norgate et al., 2007), water (Norgate and Lovel, 2004), generate more waste (Mudd, 2009), and produce more deleterious elements, such as arsenic (Schwartz et al., 2017). Additionally, copper mines of the future are more likely to be located in remote and ecologically sensitive areas (Durán et al., 2013; Vidal et al., 2013), on the lands of indigenous or tribal peoples, and in jurisdictions characterised by corruption and poverty (Rogich and Matos, 2008). Projects with these characteristics are likely to stimulate concerns from stakeholder groups, leading to increased scrutiny at the regulatory approvals and project permitting phases of project development. In this paper, we propose an expanded definition of the term "complex orebodies". For our purposes, a complex orebody is one that contains several of the above characteristics.

* Corresponding author.
E-mail address: d.kemp@smi.uq.edu.au (D. Kemp).

[1] The UN's SDGs are a collection of 17 goals set by the UN General Assembly and part of a resolution called "Transforming our World: the 2030 Agenda for Sustainable Development".

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The mining industry has historically addressed supply challenges by capitalising on rising metal prices, achieving economies of scale and investing in technological innovation (Bartos, 2007; Mudd and Jowitt, 2017). We challenge the assumption that a rise in copper price, driven by demand, will ‘unlock’ previously uneconomic orebodies. As commodity prices are not immediately sensitive to environmental, social and governance (ESG) factors, we argue that taking advantage of a rising price to rapidly unlock these orebodies will come at a cost. Reacting to a simple price rise is likely to ‘unleash’ an unacceptable suite of environmental and social impacts. This paper considers future copper supply against a broad range of complex factors.

In presenting our argument, we examine 308 of the world's largest undeveloped copper orebodies and explores the extent to which price is the principle constraint to unlocking the resource. In doing so, we develop a conceptual multi-factor risk profile of the world's future copper supply. Our preliminary analysis reveals that a significant proportion of future copper supply involves ESG risks that are not immediately price-sensitive. A rapid unlocking of these ore bodies to meet demand will have negative ramifications for the long-term availability of metals that are necessary for economic growth, human development, and the transition to a low carbon future (Erdmann and Graedel, 2011). To avoid sub-optimal outcomes, new copper projects should conduct multi-factor risk analysis, with a focus on long-term sustainability performance.

This section introduced our topic and core arguments. Sections 2 and 3 position our research in the context of global debates and literature about the role of mining in sustainable development. Section 4 describes the sample, sources of data, and the methodology we developed and applied to explore a range of complex factors. Section 5 demonstrates the prevalence of ESG risks across the future stock of known undeveloped copper orebodies. Section 6 discusses implications for the future supply of copper in light of these findings. The concluding section articulates a future agenda for applied, multi-disciplinary research.

2. Research context: global demand for copper

The use of copper to progress human development extends across several millennia. Archaeological evidence suggests that copper piping for water infrastructure was used in ancient Egypt from 2500 BC, transforming food production and sanitation systems. Some of the earliest currencies used copper coins, such as those produced in Greece and Persia from 700 BC. Monetary transactions expanded the scope and scale of business and trade beyond conventional forms of bartering and exchange. In recent centuries, the use of copper wire ushered in the Electrical Age of the 1800s (CDA, 2018). The past hundred years witnessed an increase in copper demand, largely due to global population growth (Golding and Golding, 2017). Increases in copper consumption per capita are mainly attributed to mass urbanisation and the widespread availability of copper-intensive information technologies (Binder et al., 2006). Longer-term analyses of future copper markets (e.g. Elshkaki et al., 2016; Singer, 2017) differ in their estimates of total supply and demand scenarios, but appear to work on the assumption that all identified resources will, ultimately, move into production.

During the late 2000s one of the industry's largest mining booms occurred (Connolly and Orsmond, 2011). Metal prices rose to record levels (Kelly et al., 2017), and as a result, project developments accelerated which subsequently caused costs to rise. Offering higher wages and paying a premium for services, equipment and consumables was a key mechanism for bringing new projects to market to capitalise on the high metal prices (Downes et al., 2014). However, even with record prices, major projects were stalled and even abandoned, some at great cost to the companies and communities, due to ESG issues. Well documented examples of these project include the Pascua Lama project on Chilean/Argentine border (Smith and Mccormick, 2019), the Pebble project in Alaska (Holley and Mitcham, 2016) and the Benga project in Mozambique (Ker, 2017).

In present day global commodities markets, the supply of copper is linked to demand through the copper price. The 2000s copper price rise stimulated an acceleration of mine developments all over the world (see Fig. 1). For miners, price is a key consideration in deciding whether an orebody is ‘economic’. This is heightened by the fact that miners are ‘price-takers’ – that is they have a low level of influence in determining the market price – and as a result have a strong focus on costs. [2] At a minimum, anticipated revenue must offset the capital investment required to extract, process, transport, and sell the commodity. Capital investments typically involve establishing secure operating tenure over land, the building of major infrastructure, the purchase of equipment, and maintaining a technically skilled labour force. To meet demand, the market price for copper needs to exceed the cost of overcoming the supply barriers associated with capital costs. If a conventional supply-demand logic is applied – production will follow. The question is: how far will the price rise, and will the increase be enough for developers to overcome the complex conditions they face on the ground?

A rapid spike in the global copper price could incentivize inappropriate mining developments. Mining boom developments from the 2000s that illustrate the presence of material social and environmental risks include Dikulushi in the Democratic Republic of Congo, Las Bambas in Peru, and the Ok Tedi expansion in Papua New Guinea.[4] Vidal et al. (2013, p.895) have argued that in the past, demand for metals “has been met thanks to improvements in technology and the discovery of new resources”, and that “as mines become more remote and metal grades decline, the increasing cost of mining, and, above all, increasing energy demands, will limit further expansion” of the mining industry. Prior et al. (2012, p.580), in their assessment of the market, consider “the issue of falling average ore grades over the last century is a ‘low-order’ problem when compared with the sustainability constraints associated with increased mine size and mining intensity” (p.580). Both Vidal et al. (2013) and Prior et al. (2012) suggest that future constraints on supply will require significant efforts to overcome, noting the inherent challenges of bringing low grade, high cost metals to market. According to Prior et al. (p.582), the change in costs and impacts from processing “easier, lower cost” ores for a given mineral, to “more difficult, higher cost” ores raises new types of sustainability concerns, as developers, communities and governments weigh the consequences. Based on a study of more than 2300 copper deposits, Mudd and Jowitt (2018) state the challenge in clear terms: “factors that control the conversion of resources to reserves to production (e.g. mineralogic, environmental, political, logistical, and economical) are even more

[2] In 2017, four of the 326 copper companies listed in the S&P database (2018) controlled about a third (34%) of the global copper production by tonnage, with 20 companies controlling about 70%. With this distribution, a single or a small number of companies would be unable to adjust their production rates to an extent that would influence the copper price. Likewise, in the absence of product differentiation in the copper supply chain (unlike with diamonds or metals used in jewellery), individual companies are not influential in terms of determining the copper price.

[3] Unit value ($/t)is the value in actual U.S. dollars of 1 metric ton (t) of copper. The unit value expressed in 98$/t is adjusted using the Consumer Price Index conversion factor, with 1998 as the base year.

[4] Noting that the well-documented social and environmental impacts of Ok Tedi pre-date this expansion.

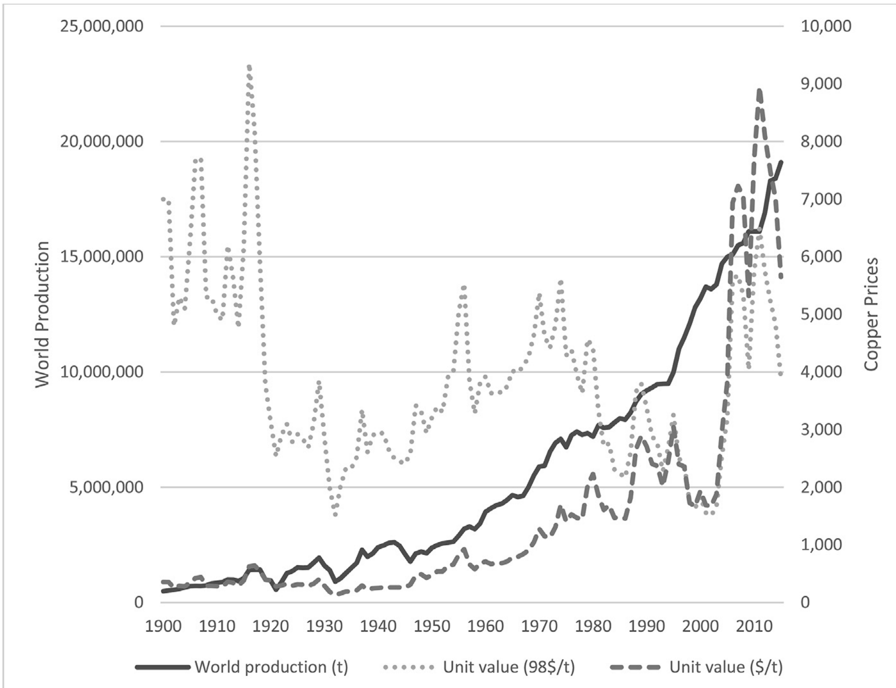

Fig. 1. Historic evolution of copper prices and global production.
Source: Kelly et al. (2017).[3]

influential [than new discoveries] in terms of the future supply of Copper" (p.1235). Taken together, this research indicates that the sustainability of future projects, and by extension the supply of metals, will depend on the ability of developers to demonstrate their social and environmental credentials at a level previously unseen in the sector.

The industry's sustainability credentials have been the subject of much critique. In the late 1990s, as the mining industry expanded into new global frontiers, these critiques focused on the industry's social and environmental impacts. Degradation of land through soil contamination, water pollution from industrial discharge, public health effects from airborne particulates, and community opposition and conflict were among the most pressing issues. Issues associated with operating industrial-scale mines in jurisdictions with weak governance and high levels of poverty and corruption were also prominent. Hilson and Murck (2000) were among the first scholars to suggest that mining companies have ample opportunity to operate more sustainably, even in the most challenging of contexts. What they articulated as an agenda for change was later reflected in the landmark report, *Breaking New Ground: Mining Minerals and Sustainable Development* (MMSD), which examined the global mining industry's contribution to sustainable development (IIED, 2002). Despite a positive response from the industry at the time of the MMSD, company sustainability strategies continue to be poorly conceived and under resourced (Buxton, 2012). In the early period following the MMSD, Jenkins (2004) drew attention to the need for mining companies to understand the complex nature of the communities in the settings in which they operate. More than a decade on, Kemp and Owen (2018) argue that this understanding is too often absent.

The global investment community has become attuned to the industry's propensity to overlook the complexity and cost of context. Failure to account for context is key driver of social risk. This includes cases of 'outbound' social risk which affects communities, rebounding onto operations in the form of 'inbound' social risk which affects mining projects (Kemp et al., 2016). These risks materialise for companies when communities protest causing delays in project approvals, or disruption to operations, and when reputational damage results in loss of investor confidence, or an inability to access capital. In light of these dynamics, investors expect mining companies to disclose risks relating to environment, social and governance factors – or ESG factors – so that they can judge the degree to which these risks are material to a company's market value. While ESG factors affect the value of a resource, our analysis ties ESG factors to the orebody, and conceptualises them as risks to project development. In tying these factors to the local context, we challenge the premise that price will moderate supply and, in doing so, demonstrate that supply is more complex than market conventions would suggest.

3. 'ESG' and the mining and sustainability literature

The previous two decades of research about large-scale mining has highlighted the range of complex factors that companies, communities and governments face in designing, developing and operating large-scale extractive projects (IIED, 2002; Ballard and Banks, 2003). In the investment community, the category of ESG increasingly refers to important risk domains not captured by conventional market indicators (van Duuren et al., 2016; Friede et al., 2015). We draw on the mining and sustainability literature to explore the types of risks that are being categorised as 'ESG'.

A broad range of environmental considerations is present in investor decision-making protocols. In the large scale mining industry, environmental risks primarily include the use and consumption of natural resources, and the degradation or contamination of those resources. Mining and mineral processing requires high volumes of water, and generates high volumes of waste and wastewater (Northey et al., 2017). The catastrophic failure of high-volume, wet tailings dams has resulted in numerous disaster events that have caused widespread environmental destruction, and loss of life (Hudson-Edwards et al., 2011; Phillips, 2015). Tailings dams also can create a complex set of long-term environmental and social issues, including water and soil contamination through seepage (Kossoff et al., 2014), and challenges for post-mining land use and rehabilitation (Mendez and Maier, 2008; Reid et al., 2009). The presence of deleterious elements, such as arsenic in copper orebodies, also pose environmental hazards and health risks (Schwartz et al., 2017). Biodiversity is an increasingly pertinent ESG issue, given the presence of large-scale copper mines in the vicinity of protected areas and zones of high biodiversity (Durán et al., 2013; Murguía et al., 2016).

The social domain refers to risks stemming from the relationship between the developer, the local community, and host society. These relationships are multi-actor and multi-faceted. Depending on the aspect of resource development being considered, the term 'stakeholders' can be interpreted as including potentially or actually affected communities, local employees, traditional authorities, suppliers or interested parties more generally (Bainton and Owen, 2018). Each of these actors, through their interactions with the project, has the potential to both experience and generate social risks. Accepting the dynamic nature of social risk and its propensity to 'rebound' between actors has been identified as a major conceptual hurdle for the industry in defining the relationship between its own activities and social issues (Kemp et al., 2016). Artisanal and small scale mining (ASM) (Hilson and McQuilken, 2014), displacement and resettlement (Owen and Kemp, 2015), project-induced in-migration (Bainton et al., 2017), and the dynamics associated with mining on or near indigenous and tribal lands (O'Faircheallaigh, 2017) are prominent considerations. These and other social risks are being recognised by the investment community as impairing asset value, and in extreme cases, preventing projects from proceeding to development (Franks et al., 2014).

The third ESG category of 'governance' is integral to most contemporary definitions of sustainable development. The UN, for instance, highlights the 'crucial link' between effective institutional frameworks and the achievement of Sustainable Development Goals (UNDP, 2015). The investor community largely focuses their analysis on corporate governance. This category includes the organisational systems, processes and mechanisms that control or guide corporate decisions and actions. Codes of conduct and policy commitments, for example, define the benchmark behaviours for matters relating to corporate disclosure and transparency, and bribery and corruption (OECD, 2017). Governance considerations that sit outside a company's direct control, but which are pertinent factors, include taxation, project approval and permitting processes, law and regulation, and the influence of political factors (Stedman and Green, 2018).

Previously considered as 'niche' topics that were tangential to mining and project development, the social, environmental and governance matters are increasingly accepted as central to understanding the potential risk profile of undeveloped copper ore bodies. Some of the largest undeveloped copper deposits illustrate the co-occurrence and entanglement between ESG issues. For example, Tampakan, in the Philippines, exhibits both the presence of arsenic and community tensions. Aynak in Afghanistan and Reko Diq in Pakistan are officially on-hold due to political and social issues. El Pachon in Argentina faces permitting challenges relating to the protection of glaciers. The low-grade Namosi deposit in Fiji, and the 2-km deep Resolution deposit in the United States present unique technical challenges, alongside a range of ESG issues. Namosi, Resolution, Pebble (US), Quellaveco (Peru), Frieda River (Papua New Guinea), and Cerro Colorado (Panama), all qualify as 'complex orebodies', in the sense that they face multiple concurrent risks across the three ESG dimensions.

4. Sample, methods and approach to analysis

Our analysis is based on a sample of 308 case records extracted from the S&P Global Market Intelligence database (the 'S&P database'). These selected records are the largest in terms of copper content, and are all 'undeveloped' copper orebodies. We refer to these orebodies as 'undeveloped' because they are either not yet in production or are in limited production. In terms of size and status, the projects in this sample are representative of the world's future copper supply. Our analysis combines information from the S&P database with public global datasets to examine a range of cross-disciplinary risk factors. This section introduces the S&P database, describes the sample, and explains our conceptual approach.

The S&P database is one of the largest, most comprehensive and up-to-date sources containing records of mining projects at all stages of development.[5] As a subscription-based service, the database is used to inform business development and investment decisions. Primary users include mining, academic, finance, legal, consulting, service and equipment manufacturing companies, and government agencies (S&P, 2018). Researchers have used the database for analysing the relationship between mining projects and specific thematic issues, including proximity to protected areas (Durán et al., 2013), biodiversity (Murguía et al., 2016), and environmental risks such as water stress and climate change (Northey et al., 2017).[6]

For copper, the S&P database contains records for approximately 9000 mining projects, accounting for 763 million tonnes of copper reserves and 1.85 billion tonnes of resources. Approximately 7000 of these entries are for projects in the pre-construction phase (i.e. between advanced exploration and construction planning), or which are in limited production (i.e. halted or delayed, or otherwise not reaching their production potential). Out of these 7000 entries, 308 met a threshold of 500 kilotons of copper metal, which across the sample, represents more than one billion tonnes of copper – about half of the 'undeveloped' deposits. Note that a threshold of 100 kilotons would have doubled the sample size but added only 84 million tonnes to the total amount of contained copper. Fig. 2 presents the global distribution of the orebodies included in the study.

Our primary aim is to develop multi-factor risk profiles for undeveloped orebodies to understand the relationship between complexity, price and project development. The twelve risk categories used to build this profile are presented in Table 1. Data for 'mineralogical' risk were sourced from 'pre-defined' fields in the project profiles of the S&P database. For the 'community', 'legal' and 'arsenic' risk categories, data were sourced from the S&P database's 'long text' fields through keyword searches. The remaining seven risk categories rely on global datasets that do not refer to copper orebodies, but which provide important contextual data about the host environment in which the mining project is located.

Copper grade and mineralogical variability are recognised components of 'mineralogical' risk (Bradshaw, 2014). 'Grade' risk was estimated using a capped copper equivalent. A copper equivalent grade was calculated based on the reported grade of copper and gold. Gold is most often associated with copper in known deposits (Nassar et al., 2012). Copper and gold prices were then used

[5] Previously called the SNL-Metals & Mining database.

[6] Note that other databases are available, including by Mudd et al. (2013), which was recently updated (Mudd and Jowitt, 2018).

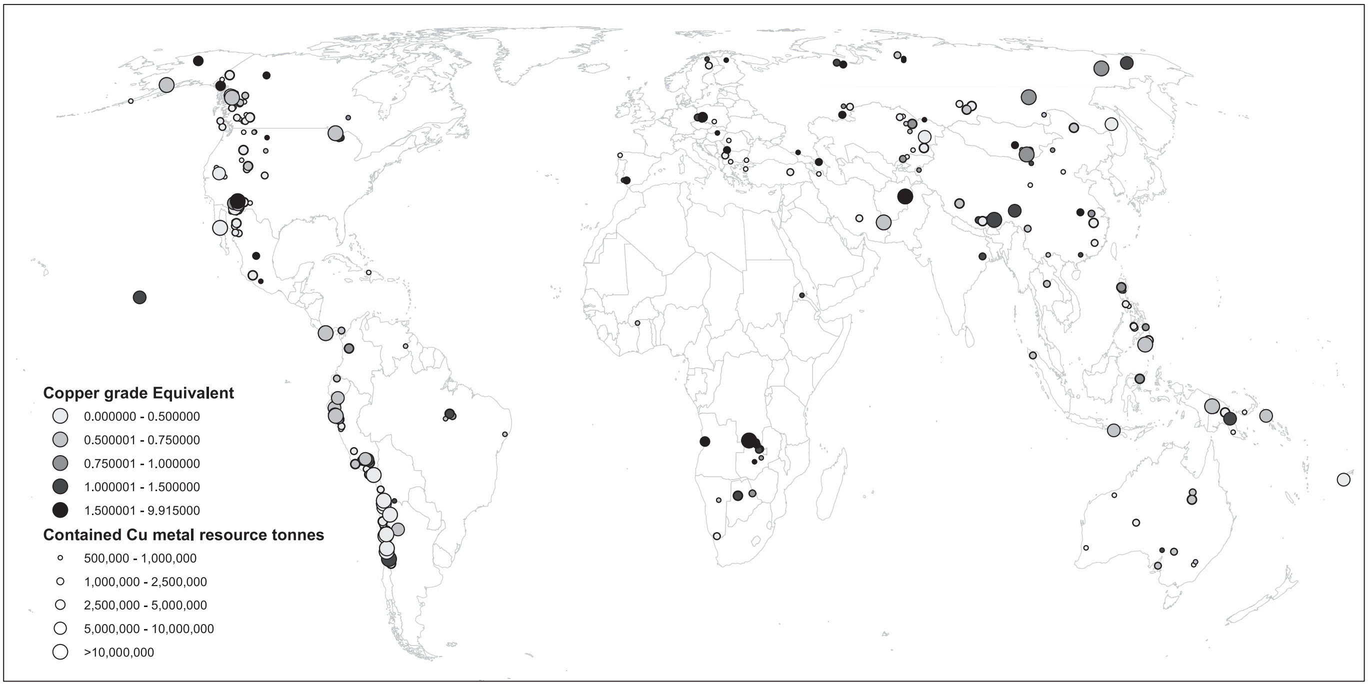

Fig. 2. Orebody location and size.

Table 1
Risk categories, type, data and source.

Risk category	Category type	Type of data	Data source/combinations
1. Grade	mineralogical	pre-defined fields	S&P database
2. Variability	mineralogical	pre-defined fields	S&P database
3. Arsenic	environmental	keyword search in long-text fields	S&P database
4. Biodiversity	environmental	public datasets	Global Terrestrial Biodiversity dataset (Jenkins et al., 2013)
5. Tailings	environmental	public datasets	Terrain Ruggedness Index (Amatulli et al., 2018); Aqueduct Water Risk Framework (flood occurrence) (Reig et al., 2013); Global Seismic Hazard Assessment Programme (SED, 2018)
6. Water	environmental	public datasets	Aqueduct Water Risk Framework (Reig et al., 2013)
7. Community	social	keyword search in long-text fields	S&P database
8. Infrastructure	social	public datasets	The Global Energy Observatory (Gupta and Shankar, 2017); Enipedia (Davis et al., 2015)
9. Land Use	social	public datasets	Permanent Cropland (FAO, 2018); Population Density (World Bank and FAO, 2018)
10. Poverty	social	public datasets	Human Development Index (UNDP, 2018)
11. Legal	governance	keyword search in long-text fields	S&P database
12. Permitting	governance	public datasets	Policy Perception Index (Stedman and Green, 2018); Ease of Doing Business Index (Djankov, 2018)

to convert gold to a copper equivalent.[7] The calculated copper (Cu) equivalent was capped, with grades greater than three per cent truncated to reduce the effect of extreme values on the mean value.[8] ‘Grade’ risk was calculated by normalising the Cu equivalent grade to a value between zero and one, and taking the inverse of this value to reflect that lower grades represented a higher risk, as below.

$$Grade\ risk = 1 - \frac{Cu_{eq}(\%)}{3\%} \tag{1}$$

‘Variability’ risk indicates a requirement for complex and costly extractive methods, and was estimated using a keyword search for common copper and accessory sulphide minerals, such as chalcopyrite and bornite. The search returned a high number of keyword appearances, indicating variability of the ore. For deposits containing multiple zones, which are often spatially and geologically distinct, the same mineral occurring in two different zones within the same deposit was counted twice because the number of zones was interpreted as adding to the complexity. Once a total count was estimated for each deposit, the data were again normalised to a value between zero and one.

$$Variability\ risk = \frac{Count\ for\ the\ deposit}{Maximum\ count - Minimum\ count} \tag{2}$$

Data for the ‘community’, ‘legal’ and ‘arsenic’ categories were sourced through keyword searches in the S&P's free text fields: ‘work history’, ‘general comments’ and ‘environmental comments’. These fields are compiled by S&P analysts by reviewing public

[7] Average prices for the year 2018 (as of December 14) were used as a basis for the calculations: USD 6150 per tonne for copper and USD 1200 per ounce for gold (LME, 2018).

[8] Capping the sample at 3% Cu excludes six deposits (grade > 3%). This represents less than 0.4% (or 21.7 Mt) of copper content.

filings including, financial and technical reports, and JORC compliant statements released by the project owner. For each category, search terms were formulated based on risk descriptions commonly used in the academic literature, and in public filings materials. Positive returns on keyword searches were checked for accuracy. Where keyword searches produced a positive return, a verification step of checking individual cases confirmed the presence of risk factors.[9] After the search returned a count of keywords per project and per risk category, the same normalisation process for 'variability' risk was applied. Standardised and geographically complete datasets were not available for these risk categories.

For the remaining risk categories, different combinations of global datasets were compiled (Table 1). Recognising that global datasets may not reflect local realities in the vicinity of each orebody, they were selected based on their coverage, completeness and resolution. For example, the land use category uses high-resolution datasets to indicate the presence of people and the main land uses on which their livelihoods depend, understanding that mining may collide with these activities. The next step in our analysis was to extract data corresponding to the location of each deposit from the global datasets. Results were again normalised to a value between zero and one, with the highest number receiving a value of one.

In the next section, we present the multi-factor risk profiles for the 308 undeveloped orebodies in the dataset. Indicative results for the largest 40 orebodies are visualised using a shading system to represent their risk intensity.

5. Findings: multi-factor risk profiles

A summary plot of the full dataset is shown in Fig. 3. Results for the top 40 deposits based on copper metal tonnage are shown in Fig. 4.

Fig. 3 shows cumulative copper tonnage sorted by decreasing 'grade' risk, plotted against the remaining normalised risk categories. Table 2 summarises the key trends across the dataset.

Fig. 4 presents a matrix of the 12 risk categories for the top 40 deposits by tonnage. The top 40 deposits account for approximately 530 million tonnes (Mt) of copper metal, or approximately 20 years on current consumption rates (Elshkaki et al., 2018). Figs. 3 and 4 both show that virtually all of the undeveloped copper deposits in the dataset suggest moderate to high levels of risk across multiple categories.

In the top 40 matrix (Fig. 4), the most prevalent risks were 'grade' and 'infrastructure', with each showing 27 deposits with moderate to high risks in these two categories. These were followed by 'water' and 'tailings', with 24 each. 'Community' and 'variability' risks showed 22 deposits each, followed by 'poverty', 'legal' and 'permitting', with 17, 16 and 14 respectively. The least common risk categories in the top 40 matrix were 'arsenic', 'biodiversity' and 'land use', with 11, 10 and 7 respectively. Other patterns of interest include an increase in the occurrence of 'community' and 'legal' risks for projects in the range of 350 Mt and 650 Mt in the cumulative tonnage plot. There was a weak trend toward higher levels of 'poverty' and 'permitting' risk toward the lower 'grade' risk end of the cumulative plot.

For the top 40 deposits, the average number of moderate to high risk types per deposit was 5.5. The minimum number of moderate to high risk types was two, and the maximum was 12. For the purposes of analysis, the risk types were divided into three broad clusters: (i) directly price sensitive; (ii) indirectly price sensitive and (iii) relatively price insensitive. Price sensitivity was used to cluster the 12 risk categories to highlight the extent to which risk factors are likely to be directly moderated by price. In the investment literature, risks are often understood as 'financing constraints' which can prevent companies from pursuing their investment objectives (Chen et al., 2007). Price movements can assist in alleviating these constraints depending on the extent to which the risk is price-sensitive.

The only directly price-sensitive risk in the dataset is 'grade'. In this cluster of risks, a change in the copper price is likely to have a direct and immediate effect. For deposits where 'grade' is the dominant risk type, an increase in price can be expected to have a positive influence on the economic viability of the project. Indirectly price-sensitive risks include 'water', 'tailings', 'variability', 'arsenic' and 'infrastructure'. A rise in the copper price could incentivise investment in more expensive risk prevention or mitigating technologies in order to improve the economic viability of a given project. Relatively price insensitive risks, include 'permitting', 'legal', 'community', 'land use', 'poverty' and 'biodiversity'. The linkage between copper price increase and risk management in this cluster of risks is not entirely absent, but is weak compared to the other two categories.

A total of 27 out of the top 40 deposits show moderate to high risks relating to low grades. All of the 40 deposits show a co-occurrence of one or more moderate to high indirectly price-sensitive risks. The average number of such risks is 2.7 per deposit. One or more moderate to high relatively price-insensitive risks are found in 34 out of the top 40 deposits. This accounts for 462 Mt out of the 530 Mt of copper metal in the top 40 (approximately 87%). A similar pattern exists across the full dataset of 308 projects, with an average number of risks per deposit of 4.9. This equates to 96% of the copper tonnes showing at least one indirectly price-sensitive risk (average of 2.1) and 87% of the copper tonnes showing at least one relatively-price-insensitive risk (average of 2.1).

A number of strong to moderate correlations are evident in the data. Strong correlations were found between 'permitting' and 'poverty' risks (0.8). 'Legal' and 'community' risks were positively correlated at 0.62. 'Poverty' and 'biodiversity' showed a relatively good correlation at 0.5. Moderate correlations (0.3−0.5) exist for 'permitting' and 'biodiversity'; 'water' and 'tailings'; 'water' and 'poverty' and 'variability' and 'arsenic'. Weak correlations (0.2−0.3) are present for 'tailings' and 'permitting'; 'tailings' and 'land use'; 'tailings' and 'poverty'; 'variability' and 'legal'; 'variability' and 'community'; and 'poverty' and 'infrastructure'.

In addition to considering correlations between pairs of risks, it is apparent that for any single given risk in most cases there is a correlation with more than one other risk category. For example, 'poverty' has a strong correlation with 'permitting', a moderate correlation with 'water' and 'biodiversity', and a weaker but still notable correlation with 'infrastructure' and 'tailings'. Likewise, 'variability' shows a moderate correlation with 'arsenic' and a weaker but notable correlation with 'legal' and 'community' risks.

Table 3 shows these findings across all of the risk categories.

These findings provide a sense of the likely 'risk intensity' across the deposits, revealing the extent to which projects will face concentrations of multiple risk factors. A total of 180 deposits in the dataset show a moderate to high 'grade' risk, corresponding to a total of 570 Mt of copper metal. Fig. 3 shows that some risk categories such as 'tailings', 'water', 'infrastructure' and 'permitting' appear in a large percentage of the deposits, whereas others such as 'variability', 'arsenic' and 'land use' are much more sporadic in their occurrence. Almost all of the deposits in the dataset appear to be

[9] The primary limitation of keyword searches in company-supplied data is not their inaccuracy, but their level of completeness due to non-disclosure.

[10] Datasets combined within the energy density indicator (unpublished work by Dr. Ballantyne).

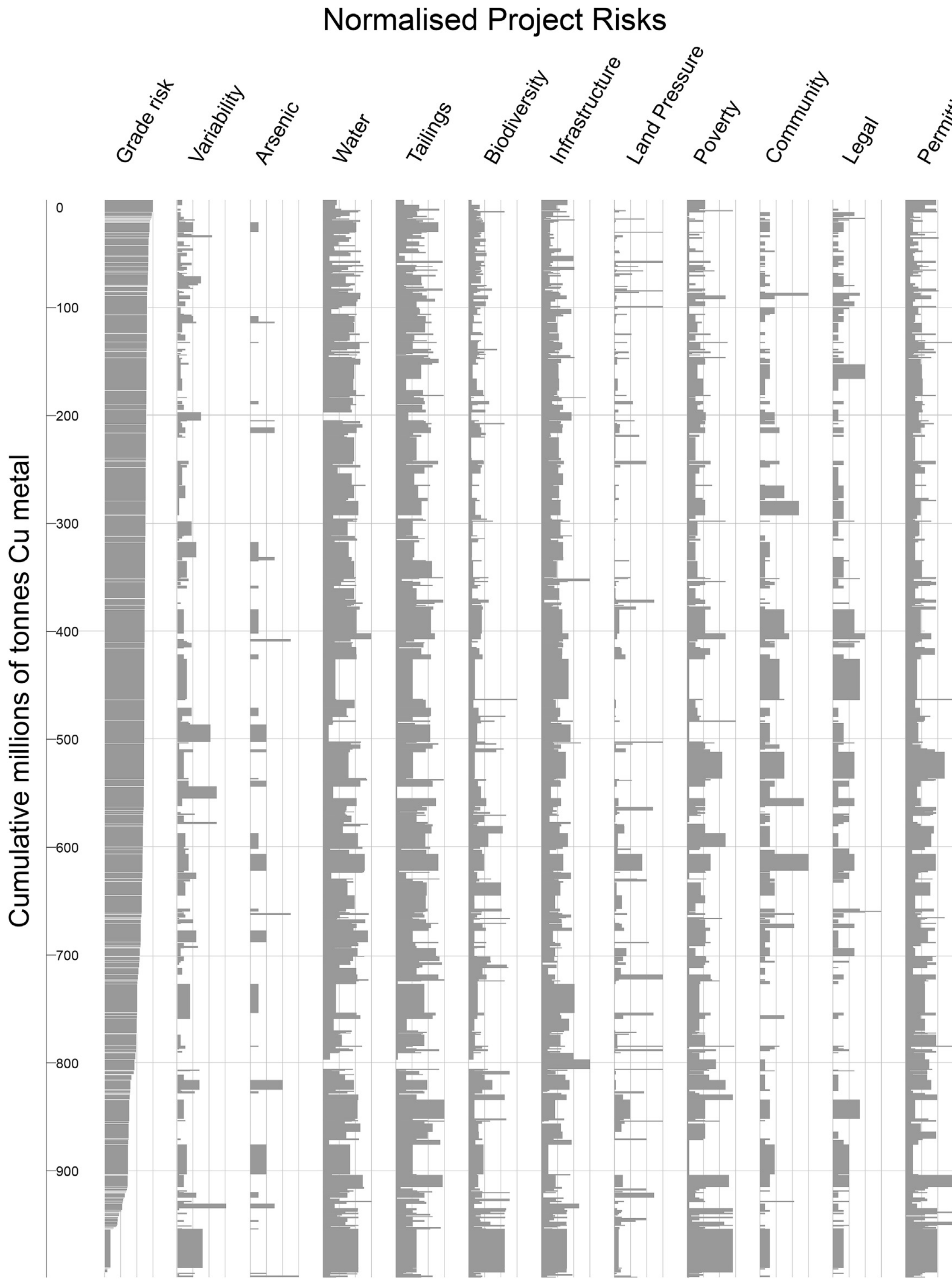

Fig. 3. Sample sorted by grade risk against normalised risk categories.

subject to a complex interplay of multiple and sometimes interrelated risks, across the risk categories.

6. Discussion: unlock or unleash?

Markets operate on the assumption that when demand exceeds supply, an upward movement in price will provide the necessary breakthrough. In this case, the market for copper metal is projected to experience significant shortfalls in supply. This is due in part to the unprecedented demand for the resource and, as we demonstrate in this paper, multiple complexities confronting a large percentage of undeveloped deposits on the supply side. While a simple price increase may provide incentives for developers to invest in technologies that allow them to overcome key risks, in the supply

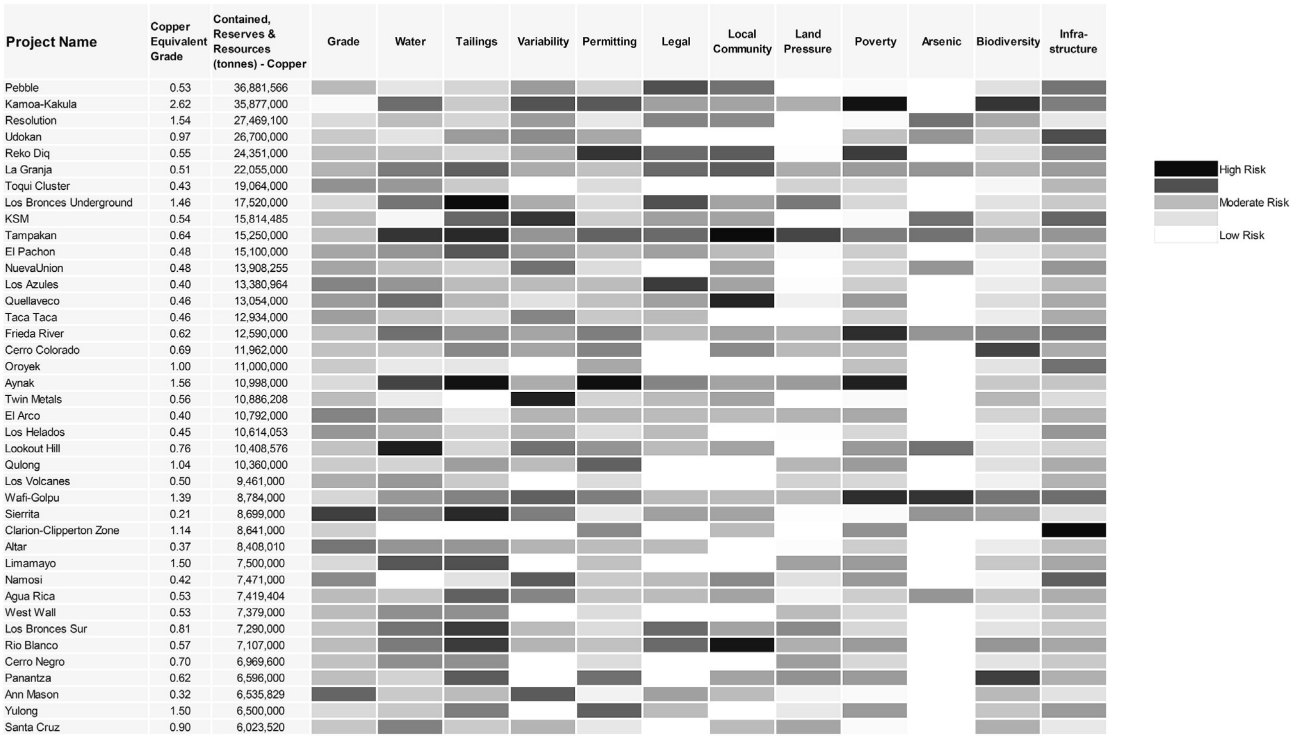

Fig. 4. Risk categories for the top 40 deposits by tonnage.

Table 2
Key trends across the dataset.

Risk	Moderate to high risk threshold	Number of Deposits above the threshold	Corresponding copper tonnage
Grade	Copper equivalent grade less than or equal to 0.60%, i.e. the global copper grade average for 2015 (derived from Mudd and Jowitt, 2018)	180	570 Mt
Water	Medium to high Aqueduct Mining Water Risk	170	584 Mt
Tailings	Terrain Ruggedness Index above 60/118; Flood occurrence from 'medium' to 'extremely high'; Seismicity Peak Ground Acceleration above 4 m/s^2	159	515 Mt
Variability	Mineral count greater than or equal to 4	118	551 Mt
Permitting	Fraser Institute Policy Perception Index of 60 or less; Ease of Doing Business ranking lower than 77th.	137	397 Mt
Legal	2 or more keywords	95	449 Mt
Community	2 or more keywords	94	489 Mt
Land Use	60 or more inhabitants per square km, or crop/pasture percentage greater than 15%	83	200 Mt
Poverty	Human Development Index less than 0.78	143	434 Mt
Arsenic	Presence of minerals/keywords	37	227 Mt
Biodiversity	Combined biodiversity in top 20th percentile	111	307 Mt
Infrastructure[10]	Energy density less than 0.1 MW/km^2	155	652 Mt

scenarios we have reviewed, the strong indication is that developers face multiple types of concurrent risk. To unlock these orebodies will require developers to innovate across a range of discipline areas.

Innovations readily emerge in response to a single problem. Where deposits are beset with multiple types of moderate to high risks, a single innovation may provide a pathway for the eventual development of the project based on ameliorating one high risk factor. Our sample suggests that the majority of undeveloped copper projects contain at least two moderate to high risk elements. We do not argue that these risks are bound to eventuate, but that the presence of multiple risks adds significantly to the design challenges of the project. This reading of what we refer to in this paper as the 'complex orebodies', highlights the type of multi-dimensional innovation needed to guarantee future supply of mining resources, and an insight into the limits of singular innovations in the face of such complexity.

Projects that proceed to development based on a simple price rise are themselves taking considerable risks. While projects may clear a development pathway in one or more key risk areas, the primary concern is that remaining risk areas carry forward into the construction and production phases of the project. Research across the disciplines shows that, left unchecked, social and environmental risks in particular generally compound over the life of mine (e.g. Laurence, 2006; Maramba et al., 2006; Pini et al., 2010). A simple price rise is unlikely to factor in distribution of liabilities amongst stakeholders over time, or the loss to the company in the form of future impairments. These dynamics are not recognised in market pricing (Edmans, 2011) and, once locked into development, companies as price-takers find themselves simultaneously managing multiple risks and keeping costs contained. Host governments do not necessarily have the means to absorb these kinds of liabilities. This is also true of local communities.

Table 3
Correlation values between risk categories.

	Water	Grade	Tailings	Variability	Permitting	Legal	Community	Land use	Poverty	Arsenic	Biodiversity	Infrastructure
Water	1.00	0.04	0.39	-0.14	0.23	0.06	0.19	0.15	0.46	0.08	0.12	-0.12
Grade	0.04	1.00	0.07	0.04	-0.19	0.10	0.10	-0.08	-0.27	-0.12	-0.26	-0.07
Tailings	0.39	0.07	1.00	-0.11	0.24	0.06	0.12	0.26	0.20	0.07	0.14	-0.15
Variability	-0.14	0.04	-0.11	1.00	-0.21	0.23	0.21	-0.07	-0.17	0.34	-0.10	0.15
Permitting	0.23	-0.19	0.24	-0.21	1.00	-0.06	0.00	0.15	0.73	-0.04	0.40	0.15
Legal	0.06	0.10	0.06	0.23	-0.06	1.00	0.62	-0.05	-0.01	0.06	0.00	0.07
Community	0.19	0.10	0.12	0.21	0.00	0.62	1.00	0.02	0.10	0.18	-0.01	0.17
Land use	0.15	-0.08	0.26	-0.07	0.15	-0.05	0.02	1.00	0.13	0.09	0.08	-0.26
Poverty	0.46	-0.27	0.20	-0.17	0.73	-0.01	0.10	0.13	1.00	0.03	0.50	0.28
Arsenic	0.08	-0.12	0.07	0.34	-0.04	0.06	0.18	0.09	0.03	1.00	-0.02	0.03
Biodiversity	0.12	-0.26	0.14	-0.10	0.40	0.00	-0.01	0.08	0.50	-0.02	1.00	-0.06
Infrastructure	-0.12	-0.07	-0.15	0.15	0.15	0.07	0.17	-0.26	0.28	0.03	-0.06	1.00

Following an increase in copper prices, the industry can expect to see positive changes for the price-sensitive risks. However, in our findings the only directly price-sensitive risk identified was ‘grade’. An improvement in market prices where ‘grade’ is the leading project risk should result in a relatively straightforward path to development. In the case of our sample, the majority of deposits where ‘grade’ was identified as a project risk also presented a minimum of one indirectly price-sensitive risk and/or a price-insensitive risk. Improvements in the market price for metals may incentivise companies to explore alternative, innovative, and more capital-intensive design options in order to manage their risk profile.

With a long-term positive outlook on demand for copper (Kuipers et al., 2018), companies may have the confidence to invest in the necessary infrastructure, waste and water technologies needed to overcome the challenges of water scarcity or abundance, tailings management, and project remoteness. Price-insensitive risk areas, such as ‘community’, ‘land use’, ‘poverty’, ‘permitting’ and ‘biodiversity’ are unlikely to change as a result of price improvements. Our analysis suggests that these factors will need to be managed independently of price movements and have the highest potential for carrying through the project lifecycle. Unlike directly price-sensitive risks, where improvements can ‘unlock’ the potential of the orebody, price-insensitive risks, if not carefully resourced and managed, can be ‘unleashed’ on the project and its broader surrounds.

The intensity and co-location of price-insensitive risks suggests that demand in this market is not as singular as ‘demand for resource’. A clear majority of risks in this risk cluster centre on either actors or natural resources that would be directly impacted by a large-scale copper mine. In this sense, some of the risk carried on the supply side reflects an alternative set of market demands about how and where resource extraction projects can and cannot operate. Consumer consciousness and advocacy campaigns over topical issues such as water management (Kemp et al., 2010), the rights of indigenous peoples (O'Faircheallaigh, 2017), and the conservation of biodiverse environments (Bebbington et al., 2018) is likewise re-shaping market demand, suggesting a far more nuanced demand spectrum has arisen. A simple increase in copper prices may provide a positive signal from one segment of the market, however, in the context of developers attempting to unlock new complex orebodies, it is important to recognise and respond to signals and demands emanating from the local environment.

Conventional market demands will no doubt have a pronounced effect on the trajectory of the orebodies analysed for this study. Developers will face the prospect of highly favourable pricing on the one hand, and increasing levels of multifaceted risk on the other. A fall in the global supply of major metals, such as copper, will have major implications for international economic growth and human development, affecting industrialised and developing countries alike (Elshkaki et al., 2018). Without adequately addressing key risk areas this could unleash social and environmental harms that neither the developer nor the host society have the capacity to contend with. Our research raises a series of pertinent questions: What constitutes responsible resource development under these circumstances? Which sustainability measures are best applied to determine whether a project should proceed? In the midst of rising prices, which types of risks are considered too high? At what point do developers leave known resources in the ground, and walk away? How are decisions about new complex orebodies best governed and regulated?

7. Conclusion: reckoning with new forms of complexity

Our dataset shows that in order to unlock the future supply of copper metals, the market will need to reckon with the new complex ore body. The sample of 308 undeveloped copper deposits indicates 96% of projected future supply present multiple forms of concurrent risk. A majority of the ESG risks analysed in this study are indirectly price-sensitive or price-insensitive, meaning that improved prices for copper metal alone, may not be sufficient for addressing the underlying complexity of the project. In some instances, a simple price rise may provide enough of an economic incentive for developers to proceed, but where projects face multiple price insensitive risks, these risks could carry through with the project. This suggests not only that the companies will need to confront a more complicated risk landscape at the project level, but also that the future supply chain for copper is itself more complex.

These findings were developed using the S&P database. The utility of the database has limits in light of claims about future challenges to the supply of key global commodities. The extent to which entries in the S&P database represents specific areas of risk is dependent on the disclosure of individual companies. This is especially problematic for risk items such as ‘arsenic’ where companies are unlikely to self-report in order to maintain the confidence of investors and local level stakeholders. While our research suggests that the risk profile for these 308 orebodies is extensive, a more complete dataset could confirm an even wider and prevalent set of multiple risks.

The consequences of not guaranteeing a future supply of copper metal are far reaching. Unlocking one part of the risk profile of a project, while leaving others unresolved may not be catastrophic on a global scale, but at the local level, unresolved risks can become deep liabilities. Demand for copper resources in the context of new complex orebodies must be viewed in relation to other demand pressures, including those that sit outside of the conventional supply-demand relationship. In addition to the demand for resources, stakeholders are exerting pressure on the industry to adopt and demonstrate a far more expansive approach to risk. Heightened demands for transparency surrounding project risks in the pre-development stage highlights the importance of improved knowledge and access to data, particularly where the risk configurations are both intense and diverse. Understanding the composition and dynamic nature of these orebodies provides an opportunity to re-think the agenda for future research and innovation in the global mining industry.

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