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# Global Challenges for Innovation in the Mining Industries

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## Introduction

People have been digging in the ground for useful minerals for thousands of years. Stone Age people dug for flints, Bronze Age people for copper. But the manner in which they have dug for minerals has changed out of all recognition. While early miners hacked small amounts of mineral from the ground with antler horns, some of today's mines employ 300 tonne trucks driven and scheduled by computers. Innovation lies at the heart of the story of mining.

Mineral materials are the foundation of modern industrial society. They are used in vast quantities to construct the infrastructure of our lives – the roads, the power stations, the airports and our homes. They are used for the durable products that we employ within this infrastructure – the cars, the planes, the hospital equipment and the refrigerators, as well as in the machinery required to produce these things. And they are used in the sophisticated gadgets that underpin the technology economy and the security products that keep us safe. The ordinary smartphone contains no less than seventy different mineral elements.

Mining ensures that we have an adequate supply of the raw materials to produce all these things, and at competitive prices. As the global population grows and standards of living of people in emerging and developing countries rises, so is demand for these mineral products increasing. In 1990, world demand for copper stood at 10.7 million tonnes. In 2017, it was over 23 million tonnes. If this rate of growth persists, by 2030 it will be 36 million tonnes.

Adding to the challenge that miners face in meeting this growing demand are two other factors. For many mineral commodities, the quality of the resources being worked is deteriorating, resulting in increased energy use and more waste. Second, the world is increasingly, and rightly, concerned about the social and environmental impacts of mining.

Innovation is central to meeting these diverse and challenging objectives. It is critical to developing techniques for finding new deposits of minerals, to enabling us to recover increasing amounts of minerals from the ground in a cost-effective manner, and to ensuring that this is done is a way that is environmentally responsible. How the industry and governments are addressing this challenge, and what they still need to do, is the subject of this book.

In this chapter, we begin by describing the mining industry and its major economic characteristics. We then discuss the role of innovation in the industry and the environment in which it takes place, and, finally, we summarize some of the major findings to emerge from the subsequent chapters in the book.

## 1.1 The Mining Industry

Mining is the business of recovering minerals from the ground and converting them into useable industrial materials and consumer products. The minerals we are talking about here are generally "hard" minerals, which is to say we exclude oil and gas but include the energy minerals coal and uranium. Within the category of hard minerals, the major subcategories are metals (and, within this, ferrous [iron-related] minerals, nonferrous metals and precious metals) and nonmetallics (construction minerals, industrial minerals and precious and semiprecious stones).

Although economically smaller than the oil and gas industry, the mining industry is still a very large, and very global, industry. Relative to the oil industry, the mining industry is much more diverse in its nature and much more geographically dispersed. Moreover, minerals are used in a much wider range of products. Whereas oil and gas are predominantly used in energy applications, minerals are used in everything from construction to soap powders. They are also the key constituents of the battery systems, wind turbines and solar panels used for the production and storage of renewable energy.

Determining the exact scale of the industry economically is not straightforward and, of course, valuations inevitably fluctuate from year

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to year along with the prices of mineral commodities. It has been estimated that the value of global mine production, at the mine gate, was around $1.3 trillion in 2014 (Lof and Ericsson, 2016). Coal accounted for around half of this, with the next biggest contributions coming from iron ore, gold and copper. If one looks at the market capitalization of the mining industry as determined on global stock markets, this is estimated to have been around $1.2 trillion at the end of 2016 (S&P Global, 2017). This equated to around 1.8 percent of the value of the global stock market at the time. It should be noted, though, that stock markets do not cover state-owned companies or the large number of small private mining concerns.

However, such broad valuations fail to capture the full economic significance of the industry for two reasons. Mineral raw materials are the starting point of long supply chains that involve substantial value adding through processing, fabrication and marketing. While the raw materials may represent only a small fraction of the value of the final marketed product, without the mineral raw material there would be no chain and no product. The value of the mineral at the mine gate is therefore just that. It says nothing about the form in which the mineral is eventually delivered to the end user or the value that has been added along the way. Very occasionally this value adding takes place at the mine but much more usually it takes place somewhere remote from it in an urban industrial center.

The second reason that global valuations offer only a partial perspective on the mining industry's economic importance is that estimates of global value fail to capture the specific importance of the mining industry to individual countries. Mining typically accounts for only a relatively small proportion of GDP (less than 10 percent) and employment (less than 5 percent) even in the world's largest mineral producing countries. However, the sector's contribution to foreign direct investment, to exports and to public finances can be very substantial indeed. The International Council on Mining and Metals (ICMM) lists 41 countries where minerals account for over 25 percent of exports by value, including 10 where they account for over 50 percent. And it lists 14 countries where receipts from mining account for more than 10 percent of government revenues (ICMM, 2016). Many of these countries are in Africa, although countries in Asia and Latin America are also represented. Such "mineral-driven" economies often have relatively few practical alternatives to mining for the promotion of their development.

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As regards the corporate structure of the mining industry, this is divided between a relatively small number of large companies and a large number of much smaller companies. An analysis conducted by the ICMM suggests that there are around 150 global and large-scale companies, often referred to as "majors"; maybe 350 intermediate companies operating in one commodity or one country, these possibly on a pathway to becoming majors; and perhaps 1,500 companies having just one mine. In addition, there are upwards of 2,500 small exploration companies, some with serious prospects and others largely speculative (ICMM, 2012a, 2012b).

The two poles of the industry have markedly different functions. The larger companies are *production focused*. They account for most of the capital of the industry, a large part of this coming in the form of debt financing, and a high proportion of its mine production. The small companies work smaller deposits or operate in niche minerals, while *exploration companies* are essentially focused on discovering and proving up mineral deposits, often with a view to selling them on to a major for development. The high risk of exploration generally means that banks will not lend to these companies, so they have to raise their finance in stock markets. The most important stock markets specializing in this kind of financing are located in Toronto, Sydney and London.

In addition to companies directly engaged in finding and developing mines, there are a large number of companies supplying the mining industry with equipment and technology, a sector commonly referred to as the mining, equipment, technology and services (METS) sector. These companies work very closely with mining companies to understand their requirements and to develop innovative solutions, be these in the design and manufacture of large earthmoving trucks or in the provision of process software. Because METS companies cover a wide range of activities and do not conveniently fit traditional industrial sector categories, the precise scale of the METS sector is hard to assess. However, for some countries it is economically significant. In Australia, which has one of the world's most developed METS sectors, it is estimated that the sector accounts for A$90 billion of sales, including A$15 billion of exports. The industry association catering for METS companies, Austmine, has over 450 members (Austmine, 2018).

Beyond the formal mining sector, there is a significant informal mining industry, populated by so-called ASMs (artisanal and small-scale miners). These are very low-tech operators, employing little capital and often unregulated. Except for a few commodities such as tin, tantalum,

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gold and precious and semi-precious stones, ASMs account for only a very small proportion of global mineral production. The sector does, however, employ a very large number of people and attract a lot of public attention. The low-tech nature of the activity means that it does not play too much of a part in the more sophisticated types of innovation which are the primary focus of this book, but there is a strand of innovation relating to so-called frugal technologies which is relevant to this sector.

### *1.1.1 Mining Activities*

While mining, as noted, is normally thought of as the business of recovering minerals from the ground, the actual digging up of minerals is in fact only one step in the process in which the mining industry engages, and only one of the spheres offering scope for innovation. The full process is illustrated in Figure 1.1. All these steps are essential for the creation of a successful mine.

The first step, and in fact the step where a lot of the value of a mineral deposit is created, is discovery. Exploration is a challenging and high-risk activity and a very small proportion of deposits looked at ever make it into production. The initial process of exploration can take many forms: the painstaking study of geological maps (where these exist), the interrogation of geological models, fly-over geophysical surveys, on-the-ground geochemical analyses and, perhaps, some exploratory drilling. Exploration can be thought of as part of the industry's R&D in as far as it represents a search for new products.

It is only if these initial investigations suggest that there might be a deposit with sufficient size and grade to make for a commercial mining operation that the project will be taken to the next stage, that of trying to prove up the deposit and establish a resource. This involves some serious drilling and, since drilling is costly (upwards of $100 a meter), it is only warranted if there is a good chance of establishing a commercial deposit. Otherwise, the exploration company would do better to cut its losses and look elsewhere.

In the event that this hurdle is surmounted, then the next task is to undertake a whole lot more drilling, at greater density, to establish


**Figure 1.1** Simplified view of the life of a mine
*Source: Author's elaboration.*

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a reserve (that part of the mineral resource which might provide the basis for an operating mine). At this point, the would-be miner will also have to give consideration to all the other elements that need to go into the creation of a working mine, the type and scale of the operation, where power to the mine will come from, how the product will be transported from the mine to market, and the establishment of a constructive dialogue with communities liable to be impacted by the mine and which might provide employees to it. The culmination of this process is usually a bankable feasibility study, an extensive and detailed analysis of the project showing that every aspect of the mine project has been addressed and demonstrating how it can make money for its owners and lenders. This is an acid test and, inevitably, a number of projects fail it.

For those projects that obtain financing then comes the matter of actually developing the mine. Given that this will commonly involve building supporting infrastructure (for example, roads, ports, power lines), the purchase of large amounts of equipment, the construction of plant and waste disposal facilities, the preparation of the ore body (for example, removal of overburden) and the training up of staff, this process can easily take three to four years.

It is only at this point that mining, as the term is commonly understood, takes place, where the digging and the bringing to the surface of the mineral-containing ore can proceed. Beyond this is the stage of processing. Very few minerals can be shipped and sold in the form in which they come out of the ground. Most need to be subject to some kind of treatment – referred to in the industry as "beneficiation" – whether this is the relatively simple matter of washing and screening (as in the case of coal) or the upgrading of the ore into a mineral concentrate through a process involving crushing, grinding and froth flotation (as in the case of copper sulfides).

For reasons of transportation costs (it is uneconomic to carry large amounts of dirt long distances), this processing stage typically takes place at the mine site and is considered integral to the activity of mining, since, without it, mined products cannot be sold. Thus the product at the mine gate will typically be an upgraded product that can be transported elsewhere for further processing or that can be sold to a third party for such processing. For metals, this further processing generally means smelting into metal and then refining to increase its purity. In some instances, the availability of local infrastructure (for example, power and ports) and relevant skills favor doing smelting and refining at or near the mine but often it does not, so these activities are carried out elsewhere, remote from the mine.

The final stage in the life of a mine is its closure. Historically, many mines were simply abandoned when they ran out of ore, with environmentally disastrous consequences. Today, this is unacceptable and companies have to start preparing for the closure of their mines in a socially and environmentally responsible fashion right at the outset of mining. Indeed it may well be the case that permission to mine in the first place is contingent on the miner satisfying the licensing authorities that they have a plan and have made sufficient financial provision for the mine's closure.

Naturally, the precise path a project follows will depend on the mineral commodity being produced. Moreover, different stages in the process are more important for some commodities than for others. For copper and gold, the value of the final refined metal product is largely (90 percent plus) created through exploration and mining. For aluminium and steel, most of the value is created through processing, the ores from which they are made, bauxite and iron ore, being relatively abundant in nature.

There are also some important geographical aspects to the process described. Mining supply chains are truly global. As already noted, while the final processing of a mineral product into finished form sometimes takes place near to the mine, in many cases it does not. A substantial proportion of the world's iron ore and copper concentrates is converted into metal – steel and refined copper respectively – at a distance from the mine and very often in another country, giving rise to a large global trade in these products. A similar situation arises with the technologies and equipment employed in mining, international products commonly developed in one country and applied or sold in another. Accordingly, to understand how the industry works, and track the influences upon it, one necessarily has to adopt a global perspective.

### *1.1.2 Economics of the Mining Industry*

The mining industry has some very specific economic characteristics which it is important to understand since they shape the way the industry works and the behavior of policy-makers toward it. They also have important implications for the targeting of innovation in the industry.

**Minerals Are Non-renewable.** Minerals are subject to depletion. Once mined, they cannot be mined again, although it may be possible to recycle the elements recovered by mining. Moreover, the quality of some mineral

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resources – which is to say their grade, the size of deposits, their depth and their ease of processing – is deteriorating as the better resources are worked out. To remain competitive, the industry has to battle continually to offset the effects of depletion through increased efficiencies and cost reductions.

**Minerals Are Unevenly Distributed Geographically.** Occurrences of minerals at sufficient concentrations to support viable mining operations are scarce. Their distribution follows the dictates of geology so miners do not have the luxury of choosing to go only to places with sound and stable institutions where infrastructure is readily available. They have to go to where the minerals are and they have to build the required plant and infrastructure in those locations, using the best available technologies wherever in the world these may have been developed. This can add substantially to upfront costs and to political risk. Minerals often have to be transported significant distances for processing and for fabrication, resulting in lengthy and complex value chains.

**Mining Is Capital Intensive.** The establishment of a mine involves large-scale expenditure, long before any revenues are generated. It is critically important to the economics of mining projects therefore that they are constructed as tightly and cost effectively as possible and that the mine and associated plant function as anticipated when the project was committed. The capital intensity of mining is also a factor encouraging the exploitation of economies of scale and in favoring projects with long lives. Given the long life of many mines, it is important to get production technologies right because, once committed, these are effectively baked into the operation for a very long time.

**Miners Are Price Takers.** Miners sell their products into global markets over which they have little or no control. Prices in the industry tend also to be highly volatile, reflecting both the sensitivity of mineral demand to changes in the rate of global economic growth and to the slow response times of mineral supply, which follows from the capital intensity of the industry. In the absence of any influence over prices, producers are required to focus on the matters over which they do have control to ensure their profitability, namely their capital spend and operating costs.

**Mining Has Intense Local Impacts.** Mining can be a powerful force for local and regional economic development, creating infrastructure, stimulating local businesses and providing jobs. However, it can also be socially and environmentally disruptive. Mining involves the removal of billions of tonnes of earth and the generation of large quantities of solid and liquid wastes. These problems are likely to get more challenging over time as mineral demand increases and public expectations of the industry rise. In addition, the generation of waste from mining is growing faster than the growth of mine production as the quality of resources being mined deteriorates. This will add to pressures on the industry to develop innovative ways to deal with the environmental consequences of mining as well as to work more closely with affected communities.

Collectively, these characteristics add up to an industry that requires a close focus on production costs and on operating in a socially and environmentally responsible manner. Moreover, the challenge of doing these things is getting greater as a result of resource depletion and growing restrictions on where and how companies in the industry can operate.

The key to unlocking cost reductions and reducing waste in a world of depleting ore resources is productivity growth – which is to say, growth in the output of mines per unit of factor inputs – driven by innovation. Historically, the industry has been remarkably successful in growing its productivity and in offsetting the effects of depletion, as evidenced by the fact that, over a very long period, the cost of producing minerals has not generally risen, and in a number cases has actually declined (Humphreys, 2013). Given the nature of mining, these advances have often come in the form of gradual and incremental improvements rather than through major breakthrough technologies. The physical laws governing mining militate against the sort of productivity improvements achievable in the technology sector as represented, for example, by Moore's law which holds that processing power for computers doubles every two years. But, over time, like compound interest, the cumulative effect of these incremental improvements has delivered dramatic increases in the mining industry's productivity.

History may or may not prove to be a reliable guide to the future. It could be that the industry will continue to deliver advances in productivity which offset the effects of depletion well into the future. But this is not something that can be taken for granted. There are strong upward pressures on capital and operating costs in the industry (Humphreys, 2015). Worryingly, it would appear from the data presented in Figure 1.2 that productivity in some major mining countries has actually declined since around 2000. There may be a cyclical element to this. Typically, industry productivity declines when commodity prices are high and producers are focused on the volume of

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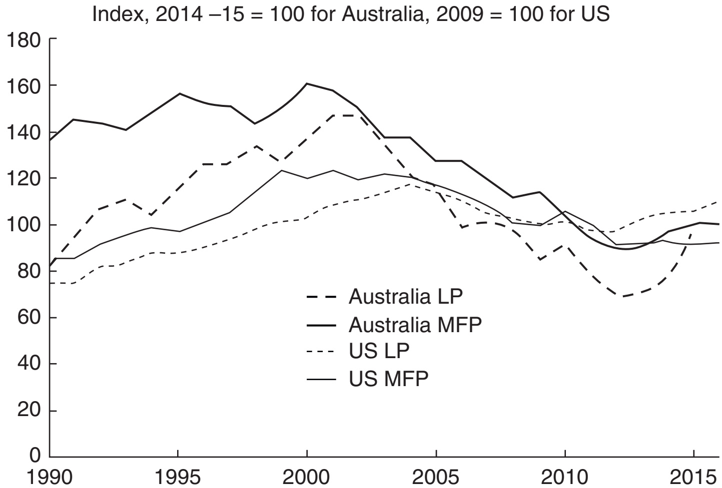


**Figure 1.2** Productivity in the Australian and US mining industries
Notes: Labor productivity (LP) measures industry output per unit of labor input. Multifactor productivity (MFP) measures output per unit of total combined inputs, including labor, capital, energy and materials.
Sources: ABS (2018) and BLS (2018).

output rather than productivity. The last few years have seen a modest reversal of the negative trend, but it cannot yet be ruled out that there are longer-term structural forces at work here too. It should also be noted that there is mounting evidence of a decline in the productivity of exploration spending. It has been estimated that the cost of discovering an ounce of gold or a tonne of base metals has roughly doubled since the 1980s (BCG, 2015).

Miners may have to look in new places for their productivity growth in future. In the past, economies of scale have provided a major contribution to productivity growth but the industry may be reaching the limits of what these can contribute. Mines are not getting bigger and the growth in the scale of mining equipment has slowed. In future, productivity growth will have to come from other sources, particularly from innovative technologies that enable miners to work "smarter." These may include the application of high-powered computing and big data, the "Internet of things" and operating technology–information technology integration, increased automation and robotics, and the use of high-powered satellites in exploration (Mining Magazine, 2016). The challenge is a substantial one and the scope for the application of innovation considerable.

## 1.2 Innovation in the Mining Industry

Innovation has been an intrinsic part of the mining industry for many centuries. History offers plenty of examples of breakthrough innovations developed for, or pioneered by, the mining industry. There is evidence of use of wooden railroads in mines as far back as the sixteenth century. The first commercial use of a steam engine was for pumping flood water from mines in the early 1700s. Alfred Nobel's dynamite rapidly spread in the mining industry after its invention in the second half of the 1800s. This is also the case of energy generation technologies applied to new infrastructures – such as dams and power plants – as mining sites often require access to large amounts of energy in remote areas. Likewise, the mining sector is a key stakeholder in transport infrastructure investments (e.g. new railways and ports), where innovation can play an important part. In recent years, mining has been the focal point for the development of autonomous haulage trucks.

Innovation in other sectors also has a "pull effect" on mining activities. The growth of certain industries feeds back up the supply chain, increasing the demand for specific mining outputs. This was the case for coal and uranium for the energy sector, iron and aluminium for the transport and construction industries, and copper, lithium and the rare earth elements for the information and technology (ICT) sector. Every spike in the specific demand of a mineral generates an opportunity for new mining activities and innovation.

As discussed in Section 1.1, innovation's main goal in the mining sector was, is and will be about improving productivity. Simply put, mining firms can increase productivity in three ways: (i) by improving efficiencies at existing mining sites, (ii) by opening new sites with a higher yield or (iii) by closing those with a lower yield. Innovations can contribute to all three ways. Innovation can increase efficiencies and reduce costs in production, processing and delivery to market at a given mining yield. It can increase the accuracy of the exploration for new mine sites or reduce the costs of the mine development. And it can reduce the financial, social and environmental impact of the closure of mines.

### *1.2.1 Applying the Innovation Economics Framework to the Mining Sector*

The following chapters in this book will address different elements of innovation economics as they apply to innovation in the mining industry. What follows is a broad depiction of the innovation economics

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framework that gives a conceptual base for these analyses. It focuses principally on the different types of mining innovation and the mining innovation ecosystem.

## Types of Mining Innovation

As in any other sector, mining firms innovate in their products, production processes or organizational practices (OECD/Eurostat, 2019; Schumpeter, 1942).

With regards to product innovation, the mining industry is a little different to other economic sectors. Many mined products – such as copper and zinc – are simple commodities with a demand insensitive to product differentiation and branding. The discovery of entirely new products is extremely rare, suggesting that the scope for product innovation in mining is very limited. However, some industrial minerals – such as borates, fluorspar or kaolin – are sold on the basis of their chemical and physical properties rather than on their elemental content, creating opportunities for the development of product variations. Precious and semi-precious stones also offer scope for developing new product variants. Furthermore, there can be new and innovative uses found for existing products, as, for example, has occurred in the new technology field. The use of rare earth elements and lithium in green energy applications might be examples of this.

However, while the discovery and development of new mined products may be rare, the discovery of new commercial deposits of existing products through exploration is an important part of the economics of the industry. In fact, when talking about product innovation in mining, there is a case to be made that the deposit or the mine is really the "product" rather than the mineral recovered from them.

Viewed in this way, a company's expenditure on exploration becomes a part of its R&D, in the sense that it is expenditure aimed at finding new, commercially exploitable, sources of a mineral, even though such expenditure may not be recognized formally as R&D. There are interesting parallels here with other industrial sectors. Mines open up, operate and close down, very much in the way that manufactured products are invented and produced before moving through to obsolescence. Similarly, just as industries like pharmaceuticals spend large amounts of money on trying to discover new marketable drugs, despite the long odds against them, so mining has to battle equally long odds in its search for commercially viable "greenfield" (i.e. new) sources of a mineral commodity. Very broadly, it has been estimated that for every thousand mineral occurrences identified, only one will be subject to exploration and of every thousand deposits explored, only one is likely to become a mine (Kreuzer and Etheridge, 2010).

Process innovation and organizational innovation are critical to the mining industry and are generally aimed at cost reduction. In many industries, the boundaries between innovation in the production processes and the organizational ones are often blurred. This is certainly the case for the mining industry. Typically, process innovation refers to any improvement of the production process within the industrial plant. These include changes to the layout, machinery and any method employed to produce a good or service. Organizational innovation includes everything that happens outside of the production plant. These include the logistics, management, financial and similar innovations.

In the case of mining, process innovation refers to any improvement happening within the mining site, while organizational innovation is any improvement of operations outside the mine premises. However, several mining innovations will easily fit both definitions. For instance, new exploration methods (e.g. a drone sending images to a computation facility) or new transport systems (e.g. a controlling system loading deep inside the mine and offloading in a port far away) are likely to happen both at the mine site and elsewhere.

## Mining Innovation Ecosystem

At the industry level, these individual innovative behaviors will combine to what can be described as a mining innovation ecosystem. The economic conditions and existing stakeholders will shape the technological development and dynamics of this ecosystem.

The constant need for cost-reducing processes and organizational innovations in the context of a scale-intensive commodity industry determines, to a large degree, how mining firms innovate (Pavitt, 1984). According to Pavitt's taxonomy, innovative mining firms are typically larger and produce a relatively high proportion of their own process technology, to which they devote a relatively high proportion of their own innovative resources. These larger companies have a relatively high level of vertical technological diversification into equipment related to their own process technology and make a relatively big contribution to all the innovations produced in their principal sectors of activity.

The mining innovation ecosystem does not only include innovative mining firms but any other stakeholder contributing to the innovation

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being undertaken in or for the sector. In addition to the mining companies, private companies supplying very specialized mining equipment and technology services – the METS companies referred to earlier – are active actors in this ecosystem. Mining companies are increasingly sourcing for cost-reducing innovations from such specialized suppliers (Bartos, 2007). As in many other large-scale industries, mining companies acquire new technologies embedded in the heavy machinery and equipment they require for their operation. Innovation may also arise from outsourced R&D and other technological services. METS innovations were and are a substantial part of the innovation being deployed in mining activities.

There are also public stakeholders such as universities, public research organizations (PROs) and government agencies participating in this ecosystem. Universities and PROs contribute to the generation of scientific and technical knowledge that eventually will crystallize into mining innovation. Universities and other higher education institutions also contribute to the diffusion of knowledge by training skilled labor to be employed in the mining industries.

Government agencies contribute by providing supporting innovation-related policies and institutions. Well-designed innovation and industrial policies aim at changing the economic incentives within an innovation ecosystem to attain a given policy objective. Governments in mining countries often attempt to make better use of their comparative economic advantage in mining-related commodities to generate spillovers downstream of mining or in other sectors. The industrial policies of industrialized mining economies such as Australia or Canada seem to have been more successfully implemented than have those in other mining developing and least-developed countries (Venables, 2016).

Similarly, innovation-related institutions such as finance, standards, safety and intellectual property, provide support for, and impose requirements on, the mining innovation ecosystem. In many countries, current regulatory frameworks have increasingly limited certain production practices both in terms of labor security and environmental practices. Such environmental and safety regulations are a motivation for innovation in the mining sector (Popp, 2003; Warhurst and Bridge, 1996). Innovations related to water treatment, $CO_2$ emissions, fracking and safety are among the typical examples. These external constraints can affect the innovation rate through the increase of cost but also through the direction of innovation projects. New environmentally friendly technologies may require a totally different approach regarding the existing technological path of given firms.

### *1.2.2 Ecosystem Interactions and Intellectual Property*

Technology transfer and diffusion plays an important role in increasing the impact of innovation on productivity. As described above, a substantial part of the innovation occurring within the mining innovation ecosystem happens through knowledge and technology flows among and within stakeholders. Typical manufacturing and technology companies will often have large centralized R&D functions, while mining innovation often arises from the specific conditions in which individual operators work and are driven through collaborations between individual business units and METS companies.

Large mining companies can centralize innovation activities up to a certain point. There are substantial cost-saving innovations that can be achieved by internalizing and centralizing R&D activities in one place. But, eventually, at least some of these innovations are transferred and adapted to the different mining sites around the world. Local adaptation of mining technologies can shift innovation incentives of stakeholders. Mineral specificities and mining sites development are likely to be more similar around the same location. Mining companies sharing the location of the same mineral may observe economies of scale in pooling R&D and engineering resources in local hubs where the technological challenges are similar. Such scenarios may shift incentives not only of private stakeholders, as governments and universities may also see the advantage of investing in common technological solutions. These common solutions only increase technological flow within and across stakeholders.

Technological flow can be part of a codified exchange, a tacit one or simply embedded in the goods or services being exchanged. The innovation ecosystem conditions shape how knowledge and technology can be appropriated. The mining sector – as many other large-scale industries – relies on a mix of know-how lead advantage, process secrecy and patents.

Keeping know-how advantages is easier when the knowledge is not easily codifiable or embeddable in a good or service. Such tacit knowledge can be crucial to mining-related innovation. The deployment of mining sites requires technical know-how and adaptability embedded in human resources (e.g. engineers) operating on site. However, technological transfer and diffusion of tacit know-how occurs from one site to the other through the mobility of skilled labor. Mining firms often include secrecy clauses in their labor contracts to avoid undesirable leakage of tacit knowledge that may reduce their lead advantage. But the enforceability is often limited according to the jurisdiction.

The increasing need for external interaction among stakeholders pushes for a higher use of the patent system. Global mining firms needing to deploy technologies at the global scale can rely on the internationalization of their patent protection for a more standardized appropriation. Locally, joint ventures to develop technical solutions with academia and competitors for the same minerals and mine site types also foster the institution of appropriation formalities such as patents. METS companies transposing other technologies to mining sector needs will also protect their technologies of reverse engineering with patents.

## 1.3 Summary of Content and Findings

The subject of mining and innovation has many facets, few of which have been subject to rigorous investigation historically. The growing interest in mining innovation and the increased availably of tools for its analysis provide an opportunity to rectify this. The contributions to this book explore what has been going on in mining innovation around the world with a view to identifying patterns and trends. To do this, they use a wide variety of approaches, datasets and methodologies. Some of the contributions focus on global industry themes; others look at individual country experiences. The combined result is a rich and original perspective on a topic of critical importance to the future direction and performance of mining.

Chapter 2 provides a broad overview of recent trends in innovation in the mining sector. It finds that R&D in the mining industry is low by comparison with many other industrial sectors although the interpretation of this finding is complicated by the matter of whether mineral exploration should considered a form of R&D. It also finds that a major part of the R&D – and innovation – in the sector is carried out, not by the mining companies themselves, but by suppliers of equipment and services to the industry, the METS sector. The chapter then proceeds to a discussion of the use of patents as a proxy for innovation before employing WIPO's database on patent filings to explore recent trends in innovation. Considering both mining companies and METS companies, it finds that the rate of patenting rose sharply in the mid-2000s: this at least partly explained by China's growing interest in mineral raw materials and its increased participation in the global patenting system. The chapter also looks at patterns of innovation in different countries in light of their particular economic characteristics and competitive advantages. Thus it finds, for example, that a mining country like Canada has a strong

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focus on innovation in upstream activities like exploration and blasting, whilst the Republic of Korea, a major importer of mined products and a supplier of mining equipment, focuses on metallurgy and automation.

Chapter 3 takes a look at the role played by foreign direct investment in the transmission of innovation in mining. More specifically, it looks at the role of mining multinational corporations in promoting innovation in the least economically developed countries. Although, for a variety of reasons, investment in mining by multinational miners in developing countries has not always proven an unqualified blessing from a development perspective, the authors of the chapter find that there is ample evidence that developing countries have generally benefited from spillovers from technologies introduced by global miners. For the full benefit of such technology transfers to be realised in the local economy, it is appears to be important that global miners and their suppliers develop their technologies in collaboration with local partners. An incentive to do this arises from the fact that mining requirements can be very site specific, creating opportunities for local technology developments. To extract the maximum benefit from technology transfer, countries need to implement policies on foreign direct investment that not only encourage the deployment of innovation but help promote linkages between foreign investors and local companies, encourage the transfer and embedding of skills in the local economy and assist with the cultivation of a local R&D capability.

The focus of Chapter 4 is innovation in the mining value chain, a term that refers to the full range of activities that firms and workers carry out to bring a mined product from its conception to end use, recycling or reuse. The topic is addressed from the perspective of Latin America, one of the most important mineral-producing regions in the world but one that has historically been heavily reliant on technologies developed elsewhere. The growing sophistication of mining in recent years has been accompanied by growth in the importance of METS firms in the value chain. While this has complicated the dynamics of the mining industry, it has also created opportunities for mining countries like those in Latin America to play a more active part in the value chain. The authors consider how innovation can be developed through the interaction of mining companies, their suppliers and other organizations active in the innovation system, such as universities and government research centers. They provide examples of technologies that have been developed in Latin America, some of these in response to specifically Latin American challenges – an example is the development of technologies for mining at

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high altitudes – and conclude by looking at schemes introduced in Chile (the World Class Suppliers and Alta Ley programs) to strengthen linkages in the value chain and to promote innovation through information exchanges between innovators and those with problems to solve and through constructive interaction amongst mining industry stakeholders.

Mined products are often bulky and transport, whether by conveyor, truck, rail or ship, can account for a substantial proportion of the delivered cost of a mineral product. The continuing globalization of mineral markets, and in particular the growing impact of China as a buyer of minerals, has further increased the importance of mineral transport, both by land and sea. Innovation is important for developing new and better ways to move mineral products around and to reduce or contain costs. This is the subject of Chapter 5, in which the authors examine in detail mining-related transport patents since 1990. They find that the share of transport-related patents in total mining patents has grown in recent years and that China has accounted for a large part of the increase, having a particular impact on innovation in conveying and rail technologies. The authors provide several specific examples of recent transport innovation. They also find a rapid increase in the rate of patenting for transport automation since 2009. An examination of forward and backward citations for mining-related transport patents reveals that there are strong flows of innovation between mining and non-mining sectors.

Mining activities are often very physically disruptive and Chapter 6 shifts the focus to mining and the environment. Its particular interest is the impact of public policy and, more specifically, the stringency of public policy on innovation in "clean" technologies in mining. To test out the relationship statistically, the authors break out from the general body of mining-related patents held by WIPO those that have a specifically environmental character. They then compile data from the OECD on the stringency of environmental policy in a range of countries, further distinguishing between policies which are market based and those which are nonmarket based ("command and control"). The statistical analysis reveals a clear association between policy stringency and innovation in clean technologies, pointing up the importance of good public policy to stimulating innovation in the mining sector. Slightly less predictably, the analysis seems to suggest that nonmarket policy instruments have been more effective in stimulating innovation than have market instruments.

Chapter 7 studies mining innovation in relation with price cycles. Two hypothesis are raised: mining innovation may be pro-cyclical therefore rising in periods of high commodity prices or countercyclical therefore boosting in periods of low prices as a cost-reducing innovative effort. The pro-cyclical effect is found to be stronger than the countercyclical one, even though the two mechanisms may coexist. In addition, long price-cycle variations affect more mining innovation than short-cycle ones. This is coherent with the long decision-making timeline associated with the mining sector, where a bulk of the technological changes happen when mines are opened or closed.

The remaining chapters of the book explore the issue of innovation and mining from a country perspective, spanning both emerging economy and advanced economy experience.

The first of these, Chapter 8, focuses on Brazil, one of the world's most important mining countries. In this chapter, the authors examine mining patents filed in Brazil over the period 2000–15. The data show local mining companies filing more patents than foreign ones, but these number are dwarfed by the patenting activity in the METS sector, a sector where foreign companies, notably those from Japan, USA, Germany and Finland, totally dominate. The authors then consider what the data reveal about the mechanisms for mining innovation in Brazil. A major contribution comes from foreign companies contracted to supply equipment and technical services to domestic mining companies or the local subsidiaries of foreign ones. With respect to innovation by local miners, this field is very much dominated by Vale, Brazil's largest mining company. A case study on Vale shows the company pursing innovation through its own in-house research, through partnerships with local METS companies, through collaboration with other domestic research bodies and universities and through its import contracts with foreign technology suppliers. The authors suggest that Brazil's high dependence on imported innovation results in an undue focus on short-term cost-reducing operational technologies and insufficient attention being paid to longer-term technologies bearing on industry fundamentals like exploration, automation and the environment.

Staying in Latin America, Chapter 9 looks at Chile, the world's largest copper producer. Chile has in recent years seen several policy initiatives intended to encourage innovation in the mining sector. The authors first examine patterns of patenting activity in Chile and note the increasingly important role played in mining innovation by the METS sector. They then employ the results of a survey undertaken amongst METS

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companies participating in a recent government scheme for promoting innovation, the EXPANDE program, to explore these companies' innovation practices and how they protect their innovations. The survey reveals that while most companies responding to the survey consider themselves to be innovative, only a minority of them rely on IP rights to protect their innovations. This result reflects not ignorance of the IP system amongst innovators but the cost of patenting and the perceived complexity of the registration process. Other factors mentioned are the preference for other forms of protection such as trade secrets or trademarks and a lack of incentive in academic institutions to engage in technological innovations. The authors suggest that a scheme for increasing the returns on IP investment might be effective in promoting an increase in IP protection.

Chapter 10 returns to the matter of how public policy helps to shape innovation, in this instance in the USA. The particular question posed here is how the MINER Act of 2006, an act intended to raise safety standards in US mines and to incentivize the development of safety technologies, impacted innovation on health and safety in US mining. The question is of considerable importance given the high-risk nature of the mining industry. To explore the topic, the authors use advanced statistical techniques to extract from WIPO's patent database a subset of data for patents relating to mineral mining in the USA and, within that, another subset relating specifically to safety-related mining patents. Using a mixture of graphical, text-based and statistical methodologies, the authors conclude that the MINER Act did indeed have a measurable impact on innovation in the sector. They are also able to point to specific safely technologies which have emerged as a result of the implementation of the Act and to demonstrate how the increase in innovation stimulated by the Act has resulted in a numeric decline in injuries and lost workdays in the US mining industry.

In Chapter 11, the authors use patent data to explore patterns of innovation in the Canadian mining sector. The patents data show that Canada has a strong upstream (exploration, blasting, processing) focus in its patenting activity, a fact that follows logically from Canada's global leadership role in mineral exploration and its use of tax incentives to promote exploration. Some innovations in the area of exploration, the data reveal, come as spillovers from the oil and gas sector. Given that innovations tend not to be discrete events but are linked thematically, the authors develop some original 3D "landscapes" to show the relationships between different patent families and pinpoint where the emphasis on patenting activity lies. Further graphics explore where in Canada patenting activity takes place and identify areas where there is evidence of innovation clusters. A final topic analyzed is the linkages between companies and other relevant institutions engaged in the patenting process. This reveals extensive collaboration between innovators, a tendency which the authors believe is leading toward a more open environment for innovation, this despite the mining industry's traditional protectiveness of their IP rights.

The final chapter, Chapter 12, looks at innovation and IP use in Australia, arguably the most dynamic country in the field of mining innovation today, and one that benefited considerably from the mining boom triggered in the 2000s by China's rapid industrialization. Australia is further distinguished by the extent to which government has been involved in the promotion of mining innovation, through the sponsorship of research institutions such as CSIRO and the CRCs (Cooperative Research Centres) and its R&D Tax Incentive scheme. The authors of the chapter employ patent data over the period 1997–2015 to investigate who has been filing mining-related patents in Australia, for what purposes and in which parts of the country. As in Canada, the data show that the primary focus of patenting in Australia is in upstream activities like exploration, mining and processing rather than in smelting and refining. They also show evidence of high levels of patenting by foreign companies (notably from the USA, the UK and Japan) in Australia, and of extensive collaboration between these foreign companies and Australian ones. While the trend in patenting has been strongly upwards through most of the period covered by the data, since 2012 the rate of patenting has dropped sharply, more sharply than the authors would have expected.

## 1.4 Concluding Thoughts

The issue of innovation in mining has never been more important. Growing mineral demand coupled with the declining quality of existing reserves and demands for increased environmental performance, require a continuous effort to raise the productivity of mining and to improve the manner of its operation. Several themes emerge from the pages of this book that can help achieve a better understanding of how innovation operates in different parts of the world and where attention should be focused to meet the demands of the future.

It is evident that the technological basis of the industry is changing. The acceleration of mining-related patenting from the mid-2000s onwards may partly reflect the impact of China but probably also reflects the advent of a new technological wave, sometimes referred to as Industry 4.0. Modern (digital) technologies offer significant potential to boost the productivity of exploration and to optimize mine-operating practices, amongst other things. This requires mining companies to supplement their traditional discovery and earth-moving skills with skills drawn from other technologies and other fields. The shift in the technological basis of the industry is illustrated by statistical analysis showing that the METS sector is playing a growing role in the mining industry, a role that appears destined to get still larger.

This undoubtedly complicates the supply chain of the industry but it also creates opportunities. Historically, mining companies have brought technologies they need with them and have been responsible for significant technology transfers to mineral host countries in developing countries. This has not always however been a very efficient or effective process. Since much mining technology is not generic, but needs to be developed in relation to a specific problem in a specific location, there is a growing opportunity for host countries to play an active part in innovation and in the development of new technologies.

Another theme to emerge from the book is the important role that governments can play in the promotion of innovation. One obvious way of doing this, of course, is through the operation of effective and well-administered patents systems. However, it goes much further than this. As the examples of Australia, Canada, Brazil and Chile in the book show, government can play a positive part in the promotion of innovation through targeted tax incentives, through support for research institutions and by sponsoring schemes that bring together those with a part to play in the innovation process whether these be miners or policy-makers with problems to solve, or METS companies or research bodies (including universities) with solutions to offer.

What is clear from the analyses presented here is that, while there is much good work going on, there is much that remains to be done. Innovation holds the key to the mining industry's ability to continue to deliver a reliable supply of mineral raw materials in a cost-effective and socially acceptable manner. This book does not hold all the answers as to how this can be done but it hopefully makes a small contribution to this by shedding light on recent trends in innovation, highlighting some of the key issues to be addressed and providing some pointers on what those in industry and government should be doing to promote creative thinking and innovative behaviours.

## References

ABS (2018). Estimates of industry multifactor productivity, Australian Bureau of Statistics. www.abs.gov.au

Arundel, A., and I. Kabla (1998). What Percentage of Innovations Are Patented? Empirical estimates for European firms. *Research Policy*, 27 (2 June), 127–41.

Austmine (2018). www.austmine.com.au

Bartos, P. J. (2007). Is Mining a High-Tech Industry? Investigations into innovation and productivity advance. *Resources Policy*, 32 (4 December), 149–58.

BCG (2015). Tackling the Crisis in Mineral Exploration, Boston Consulting Group 30 June 2015. www.bcgperspectives.com

BLS (2018). Data for "Mining, except oil and gas" (NAICS 212) US Bureau of Labour Statistics. www.bls.gov

Canuto, O. (2014): The Commodity Super Cycle: Is this time different?, in World Bank Economic Premise Series 2014 (150).

Francis, E. (2015). The Australian Mining Industry: More than just shovels and being the lucky country, IP Australia.

Freeman, C. (1994). The Economics of Technical Change. *Cambridge Journal of Economics* 18 (5), 463–514.

Humphreys, D. (2013). Long Run Availability of Mineral Commodities. *Mineral Economics*, 26 (12), 1–11.

Humphreys, D. (2015). The Remaking of the Mining Industry. Basingstoke: Palgrave Macmillan.

ICMM (2012a). The Role of Mining in National Economies. London: International Council on Mining and Metals (ICMM). www.icmm.com

ICMM (2012b). Trends in the Mining and Metals Industry. www.icmm.com

ICMM (2014). The Role of Mining in National Economies (2nd ed.). London, UK: International Council on Mining and Metals (ICMM). www.icmm.com

ICMM (2016). Role of Mining in National Economies. www.icmm.com

IMF (2015). World Economic Outlook, October 2015: Adjusting to lower commodity prices, Washington, DC: International Monetary Fund.

Kreuzer, O., and M. A. Etheridge (2010). Risk and Uncertainty in Mineral Exploration: Implications for valuing mineral exploration properties. AIG News, 100, May 2010. www.aig.org.au

Lof, O., and M. Ericsson (2016). Extractives for Development, UN University/ WIDER. www.wider.unu.edu

Mining Magazine (2016). Mining Technology and the Culture of Change, September 2016.

OECD/Eurostat (2019). Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th ed., The Measurement of Scientific, Technological and Innovation Activities. Paris/Eurostat, Luxembourg: OECD Publishing. https://doi.org/10.1787/9789264304604-en

Pavitt, K. (1984). Sectoral Patterns of Technical Change: Towards a taxonomy and a theory. *Research Policy* 13 (6, December), 343–73.

Popp, D. (2003). Pollution Control Innovations and the Clean Air Act of 1990. *Journal of Policy Analysis and Management* 22 (4, September 1), 641–60.

Radjou, N., and J. Pradhu (2014). Frugal Innovation: How to do more with less. *The Economist*.

S&P Global (2017). State of the Market: Mining Q4-2016. https://pages.marketintelligence.spglobal.com

Scherer, F. M. (1982). Inter-Industry Technology Flows in the United States. *Research Policy*, 11 (4, August 1), 227–45.

Scherer, F. (1984). Using Linked Patent and R&D Data to Measure Interindustry Technology Flows, in Zvi Griliches (ed.), R&D, Patents, and Productivity. Chicago: University of Chicago Press, pp. 417–64.

Schumpeter, J. A. (1942) Capitalism, Socialism and Democracy. London: Routledge Classics. Reedited in 2015.

Townsend, J. (1980). Innovation in Coal-Mining Machinery: The case of the Anderton shearer loader, in Pavitt, K., (ed.), Technical Innovation and British Economic Performance. London: Palgrave Macmillan, pp. 142–58.

Venables, A. J. (2016). Using Natural Resources for Development: Why has it proven so difficult? *Journal of Economic Perspectives* 30 (1 February), 161–84.

Warhurst, A., and Bridge, G. (1996). Improving Environmental Performance through Innovation: Recent trends in the mining industry. *Minerals Engineering* 9 (9), 907–21. https://doi.org/10.1016/0892-6875(96)00083-0