Innovations in mineral exploration:

Targets, methods and organization since the first globalization period

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Abstract

This paper provides an overview of the history of innovation in the mining exploration industry since its rise at the end of the nineteenth century. Innovation in exploration is divided into the following: (1) the target model itself, including the terrain and type of deposit; (2) the methods or technologies for discovering and defining the deposits; and (3) the organization of exploration, including the people involved.

Target models evolve in response to the need for new metals, the development of new extraction processes, the price of metals, the opening of new territories to exploration, and unexpected discoveries. Each model grows from pure description to a more genetic interpretation, resulting in the reorganization of ore deposit classification. Methods develop from surface prospecting to geological analogies, then to applied fundamental breakthroughs in exploration involving technologies in the fields of geophysics, geochemistry, geodynamics and information. The organization of exploration is continually reshaped, starting with the development of Taylor-style mining exploration teams within companies, evolving into the segmentation of knowledge and value chains between service and production through the institution of junior mining companies.

INTRODUCTION

In 2010, more than $12 billion[1] was spent on mineral exploration, excluding iron, aluminum, coal and hydrocarbons. This was the second-highest amount since the 2008 peak of $14.4 billion. The mineral exploration sector, like the rest of the mining industry, is experiencing a boom in activity that has been correlated with the onset of a super-cycle (Heap, 2005).

Although exploration represents usually less than 10% of the total budget in the full mining cycle, it marks the entry point into the mineral resource domain. In order to produce metals or raw materials, we need to discover more resources in the Earth's crust, which essentially represents the fundamental process initiating the industry. Over the last 15 years, the rate of deposit discovery has apparently declined (Blain, 2000; McKeith et al., 2010) and concerns have been raised about the need to sustain the process through more innovation. Innovation generally refers to the creation of better or more effective products, processes, technologies or ideas that are accepted by markets, governments and society. Innovation differs from invention or renovation in that it generally signifies a substantial positive change compared to incremental changes. By virtue of its entry position in the mining chain, mineral exploration is fundamentally an innovation process (Anon., 2011).

The metal industry is classified as a medium-low-tech industry, typical of an old-style economy (OECD, 2002). The innovation rate of metal mining companies compares directly with rates associated with general manufacturing over the last 50 years. In terms of innovation, mining appears to have far more in common with mature manufacturing industries than it does with the high-tech sector (Bartos, 2007, 2008). The level of intensity of worldwide research and development in the mineral resource sector falls below the average of other industries (Filippou and King, 2011). Mining development is a very risky business due to fluctuations in metal prices, and innovation adds another risk factor. It has been suggested that the innovation rate of an industrial branch can be

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[1] All dollar amounts in US dollars.

correlated with the speed of the end-products cycle (Brzustowski, oral communication, 2005), which is fairly low for metal products — almost the same as it was 3,000 years ago for most base metals. The highly concentrated mining industry is also less innovative because of the resistance of large enterprises to change their practice. In his landmark paper on the most important elements for discovery in the Circum Pacific region from 1970 to 1995, Sillitoe (1995) did not list innovation. Sillitoe and Thompson (2006) reviewed and analyzed the role played by changes in mineral exploration over the last 50 years and emphasized, in broader terms, the perpetuation of the same exploration approach.

However, new technology is important for every aspect of mining activity from prospecting to extraction to processing (Australian Financial Review, 21 March 2005). Innovations in mineral exploration have often been undervalued and even neglected. Canadian and Australian metrics show that innovation indicators may not be well documented in the natural resources industry because of their diversity and lack of specificity (Hall, 2002; Sharpe and Guilbaud, 2005). The classic measurements of innovation in the economy centers on fiscal metrics, research output (publications and patents) and the training of highly qualified people (Lavoie, 2007). However, these instruments do not provide a complete description of innovation in mineral resources (Natural Resources Canada, 2011) mainly because there is some confusion about the nature and role of innovation in the exploration phase of the mining industry. Upstill and Hall (2006) challenged the classification of the mining industry as low-tech because of the lack of consideration for exploration phases that should be included in the innovation metrics. For instance, exploration expenses in Québec were roughly $483 million in 2010, representing 7.3% of the $6.6-billion total for production costs.

By comparing R&D (research and development) and E&D processes (exploration and discovery), Hall and Redwood (2006) demonstrated that they share the same low success rate. Blain (2000) summarizes 50 years of trends in minerals discovery, clearly showing that the overall discovery rate rose during the 1950s and 1960s, peaked in the 1980s, and fell during the late 1980s and through the 1990s. Such discovery booms appear to be independent of metal price.

This paper first proposes a clarification of the concept of innovation in mineral exploration by distinguishing three different types of innovation related to targets, methods and organization. It then presents the long-term evolution of the innovation chain in the mining exploration industry, including how its structure evolved since the second industrial revolution at the end of the nineteenth century (for the history of mining prior to this period, see Lynch, 2002, among others). Finally, the role of continuous improvements and disruptive innovations in mining exploration, and their relationship to the development of the third period of globalization, is discussed.

A CLASSIFICATION OF MINING EXPLORATION INNOVATIONS

Mineral exploration is the process of finding ore deposits; that is, economic concentrations of ore (Jébrak and Marcoux, 2008). It relies entirely on innovation, as the search for deposits is based on the origination of an idea and its transformation into an economic mine extracting valuable products. There are several ways to classify innovations that could either be considered a process or a result. The father of the concept of creative destruction through innovation, Schumpeter (1950), identified five types of innovation: a new good, a new method of production, a new market, a new source of supply and a new form of organization. A huge amount of literature has been devoted to the definition of innovation from different perspectives (Godin, 2008).

We propose to distinguish three major fields of innovation in mining exploration: (1) the target model itself, including the terrain and type of deposit; (2) the methods or technologies used to discover and define the deposits; and (3) the organization of exploration. Target innovations may be considered the equivalent of “product innovations” in the manufacturing industry (Murmann and Frenken, 2006), whereas technology-based innovations represent “process innovations.”

Target innovations

Target innovations allow new styles of deposits and new zones of exploration to be defined. They usually correspond to the very first step of exploration, when geological ideas are encapsulated into land positions secured by claims and other mining tenements.

It is the very first indication of the legal protection of an intellectual and partly physical property.

New styles of deposits are conceived using the ore-deposit model (Cox and Singer, 1986; Roberts and Sheahan, 1988; Kirkham et al., 1993; Eckstrand et al., 1995; Jébrak and Marcoux, 2008). This idea was developed within the German tradition in the nineteenth century (Von Cotta, 1870). They are defined by the continuous development and integration of data and interpretation of newly discovered deposits, and the understanding of metallogenic processes. Therefore, target innovations are grounded in ore deposit research (i.e., metallogenic studies) and the heuristic reasoning that constitutes the development of an ore deposit model. There are several levels of modeling, from purely descriptive, enhancing the specific geological elements of a mineral deposit, to more genetic, explaining the connection between the geological environment and the mechanism of concentration (Ridge, 1983). Most of them remain qualitative because the flux of elements and the duration of the process are still poorly known for most metallic deposits. Quantitative descriptive models have been set up mainly by geological surveys, providing the grade and tonnage distribution for various types of mineral deposits (Cox and Singer, 1986; Singer, 1993, 2010; Laznicka, 1999; Pélissonier, 2001).

Questions have occasionally been raised about the value of metallogenic research in mineral exploration, creating opposition between proponents of pragmatic versus model-driven styles of exploration (Davis, 1988). Little credit has been given to geological reasoning in comparison to geophysics and geochemistry. The discovery of a mineral deposit should be distinguished from the discovery of a new type of deposit. On the one hand, there is no doubt about the key role played by descriptive geologic models in mineral discovery for almost a century now. They mainly used analogies for geological environments and/or mineralization. On the another hand, the discovery of a new type of mineral deposit has seldom relied on genetic understanding: most new deposit types have been initiated by serendipity, by the unexpected detection of mineral concentration using indirect methods, such as geochemical and geophysical techniques, or even false geological reasoning. An exception is the uranium exploration industry where an understanding of possible metallogenic processes, and not the typological approach, has been used with success by the French school of thinking (CEA-COGEMA-AREVA). As a consequence, deposit-type discoveries using indirect methods have almost always preceded the establishment of a model. The Carlin invisible gold model was developed as the possible equivalent of low-grade porphyry copper by Newmont Mining, but the deposits of Nevada were mined largely before its conceptualization as a new deposit model (Radtke and Dickson, 1976). Olympic Dam, another archetypical new model (Iron Oxide Gold Copper deposit), was discovered using magnetic and gravimetric techniques during the search for sedimentary-hosted black shale copper deposits (Woodall, 1993; Haynes, 2006). Additionally, Challenger, a new style of pegmatitic gold concentration recently discovered in South Australia, was the result of follow-up work on a geochemical soil anomaly, and the modeling of this new deposit type is still in its infancy (Tomkins and Mavrogenes, 2002). As the level of understanding grows for a model, it is used more and more by other mining companies looking for the same targets. Therefore, constant dialogue occurs along the innovation chain from academics to end users.

The main character of target innovation is its ability to be transferred, almost directly, from academics to the geological management of an exploration company. Scientific discoveries flow almost directly into applications without technological developments. From theory-based research (usually fundamental geochemistry, less often structural geology), concepts are transferred to ore deposit geologists and then to the industry. The users are both field geologists and exploration managers in search of new ground to stake and new targets to drill. Thus the knowledge, both theoretical and practical, is the result of a co-construction, where data flows mainly from field studies by an industry that communicates with academics. Such input could be informal, during field visits or conferences, or more formal, with the establishment of research partnerships between universities and mining companies as part of a bilateral project or through a consortium structure. Models could be translated into a computer-based approach using GIS, databases or specific software.

The intensity, and thus the cost, of the development phase are low. It does not require development laboratories and scaling adaptations. Commercialization is also limited. Although some of the intellectual property could be efficiently managed by some consortia, most of the knowledge is in the public domain, and the principal vectors of dissemination are publications, congresses, short courses, field trips and the formation of highly qualified people. Because the innovation chain is short, it usually takes little time or money to be transferred from academics to end users.

Target innovations have not been well recognized in national innovation statistics. Although academic work on models is usually published in international papers, no patent is recorded. The same situation has been described for “service innovation,” used in the tertiary industry (Gallouj, 2003), reflecting the fact that exploration activities could be considered as a service activity for mining producers.

Technology-based innovations

Technology-based innovations correspond to the development of new techniques used by exploration geologists. These techniques could be low-tech or high-tech, from mechanical improvements in drilling technology to sophisticated analytical tools. Most of the time, they address the direct challenges of exploration, like enhancing a signal or speeding up the exploration process, to reduce both the overall cost of discovery and the risk.

Enhancing detection signals is of major importance. Vast areas of the Earth have never been mapped in detail, especially in the Arctic/Antarctic regions and on the African, South American and Asian continents. Surface indications that deposits lie just beneath the surface can be very inconspicuous, and the ability to detect regions of interest or direct expressions of mineralization is a key component of any regional, greenfield-stage exploration. Moreover, in already known mineral districts, frontier deposits are found at ever-deeper depths, and their signatures, if any, are more difficult to recognize. Several examples of such innovations have recently been developed, such as detailed satellite imagery, with centimeter-definition and multispectral capabilities, or airborne gravimeters that are able to detect subtle changes in the gravity field around concentrations of economic minerals.

Speeding up the exploration process has also been a key component of innovation not only because it reduces costs (for instance, quickly obtaining results during fieldwork in remote areas), but also because the economic rhythm and rapid changes of the economic context require exploration to respond with the same tempo as that of the financial markets. The development of field analyzers, such as shortwave infrared analyzers capable of distinguishing clay alteration, or portable XRF analyzers capable of analyzing several elements *in situ*, have allowed the exploration industry to change its way of working (Herman et al., 2001; Peter et al., 2009). The treatment of 2D or 3D spatial data using geologic and mining software programs, often part of mineral deposit modeling (Carranza et al., 1999), have also considerably sped up the report-writing step while leading to a better understanding of the spatial organization of orebodies and their environments.

Two subtypes of innovation can be recognized: software- and hardware-based. Software-based innovations are frequently developed by universities or research consortia. They are designed to be used by exploration geologists or geophysicists, and are mostly devoted to helping with the interpretation of geochemical or geophysical data, from simple treatments to complex inversion procedures. Several geostatistical programs also allow sophisticated mathematical approaches to be carried out on personal computers. These innovations, although requiring considerable research, do not require scaling in a pilot plant. They are sometimes based on research in connected fields — artificial intelligence, for instance — which were developed early on in ore geology by the establishment of production rules (Campbell et al., 1982; Jébrak and Loesner, 1987), and could be effectively used in geographic information systems for targeting deposits after their development in other fields. Their cost thus remains accessible to the community, and they may generate some profitability in spite of their small market.

Hardware-based innovations have mostly been developed outside the mineral industry. That is the case, for instance, for analytical instruments or spatial technologies, often developed for military or general purposes. This is likely because mining exploration remains a small application domain, a niche market that cannot compete with larger domains such as the pharmaceutical or military industries. Several sector-specific analytical instruments have been developed, however, particularly in the field of geophysics, and could see applications in both mining and petroleum exploration.

Technology innovations have likely had the biggest impact on the exploration industry since the second industrial revolution. The post-war boom in the detection of massive sulfide deposits that constitute major base metal producers in Eastern Canada is directly related to the development of airborne electromagnetic techniques (Lulin, 1990). The first Landsat images were immediately used by explorers in the 1970s (Trengove, 1979). It's clear that the discovery of diamonds in the Canadian Shield resulted from the development of the mineral indicator technique (Gurney, 1984). More recently, the development of inversion software for gravimetric signals has improved drilling accuracy at the Prominent Hill copper-gold deposit in South Australia (Belperio et al., 2007). A recent survey shows that this kind of innovation was cited as one of the most important innovations of the last ten years (Jébrak, 2011).

Organization of exploration

Organizational innovations were only recognized fairly recently. Innovation can move beyond products and processes to include any type of change within an organization (Cooke et al, 1997). It represents a major area of innovation because it provides the needed ecosystem for other types of innovation. Conversely, organizations can be challenged by disruptive technological innovation.

Organizational innovation can be conceived within the structure of exploration activities or at the scale of the exploration system, involving governments, firms and academia.

Exploration, as the starting point for mining, was long considered the responsibility of mining engineers. The progressive construction of knowledge, in the beginning of the twentieth century, led to the formation of geological exploration teams with their own concepts and methodology. However, this was a very slow process, and it was only after the World War I that independent geological exploration services were clearly defined.

The organization of exploration followed a standardized set of rules for more than fifty years, with well-defined steps from grassroots exploration to the investigation of mineral occurrences, exposure by trenching, definition drilling and finally mining. This structured approach is necessary to define the risks better for investors who often have little knowledge of the multiple techniques involved in ore deposit exploration. This step-by-step methodology and the resulting need for pyramidal administration at the often widespread geographic centers of large companies meant that some managing traditions were pushed into a rather rigid organization of exploration work. In 1976, Miller was already complaining about the frustrating world of exploration geologists. An even more structured organization was set up in communist countries with inflexible approaches, such as the Chinese Gold Army. Ironically, the users that represented the purest Taylor-type compartmentalized approach were the Soviet geological teams, where information was kept confidential and there was almost no communication between the top authorities in charge of mineral evaluation in Moscow and their field exploration geologists. This type of organization has also been promoted by national mining laws that use the focusing approach of mineral exploration to define zones, duties and fees.

The technological revolutions of the past 20 years, especially the development of the Internet, have led to drastic changes in the organization of exploration, and a shift from pyramidal to more organic structures and network-centric organizations. Companies and institutions alike have developed significant organizational innovations in the broad sense (Lam, 2010). These innovations have improved the quality of data management and accelerated the processes involved. Two examples that took place ten years ago illustrate this shift.

The first occurred in 2001, when Goldcorp offered $575,000 in prize money to exploration experts anywhere in the world to help find the next six million ounces of gold at its orogenic-type Red Lake gold mine in Ontario, Canada (Tapscott and Williams, 2006). Using the Internet, the corporation made its geological database (400 Mb) and software available for interested parties to visualize and analyze the data. Some 1,400 companies, consultants, agencies and universities from 50 countries registered for the challenge. The winner was Fractal Graphics, an Australian consulting company that developed 3D modeling expertise, resulting in part from its collaboration with the CSIRO Division of Geomechanics. This was a clear illustration of the knowledge management movement from a secretive, internal and physically protected way of working to open, participative and legally protected.

The same year, in 2001, the Government of Québec decided to change its mining law to facilitate the staking of mineral properties. As in many mining countries with a Californian tradition, staking took place in the form of planting a post at each of the four corners of a claim, either by cutting down a small tree on site to whittle into a post or by carrying claim posts into the field. The claim was then registered with the provincial mining registry. Québec's Ministry of Natural Resources and Wildlife created a new way to acquire claims through "map designation." Explorers can acquire a mining property directly through the ministry's website using geographic coordinates, and electronically pay the required fees. This approach speeds up the process, allowing claims to be taken almost instantaneously, from anywhere in the world, reducing the cost for both the administration and the mining companies. As with the Goldcorp case, it illustrates the use of a new technical support (i.e., the Internet) to implement a structural change in the organization, with a far-reaching implication for others besides the traditional partners and an acceleration of communication processes.

Innovations in exploration organizations remain poorly documented because they are kept in the archives of mining companies and the government. It could be deciphered by analyzing the international evolution of mining codes over the last century, but this task is beyond the scope of the present paper.

EVOLUTION OF THE INNOVATION CHAIN

Although exploration has been an essential activity since the rise of humanity, organized prospecting activities only appeared at the end of the Middle Ages in Europe, with the key work of Georg Bauer, or Agricola, in the Saxon Highlands in 1556. The scientific approach of geology was developed during the nineteenth century, especially in Europe and America, and has been summarized several times (Ellenberger, 1994; Gohau, 1990; Rabinovitch, 2000). Geological principles slowly took prominence in the prospecting process. For a long time, mineral deposits were considered an act of God, or the effect of exotic processes. Lower Canada was considered by some specialists during the reign of Louis XIV to be of poor mining potential because of the lack of warm sun, which was supposed as generating the gold deposits. The book *Principles of Geology* by Charles

Lyell in 1833 constituted a milestone for the emergence of a new discipline: the application of scientific knowledge to an industrial process. Prior to the 1870s and 1880s, nearly all of the significant mineral deposits in Canada were discovered accidentally by individuals not actively searching for deposits (Cranstone, 2002). Mineral exploration appeared with the establishment of a more intensive, organized and professional form of mineral prospecting. The innovation chain in the mining exploration segment is directly tied to the progress of the Earth Sciences.

The narrative of the mining exploration innovation chain can be organized according to the super-cycle concept (Hocquart and Samama, 2006; Radetzki, 2006; Lyons, 2010). A super-cycle is defined as "a prolonged long-trend rise in real commodity prices, driven by urbanization and industrialization of a major economy" (Heap, 2005). This concept could be extended to large globalization events because industrialization is itself dependent on an increase in the population, the removal of barriers to free trade and the tighter integration of national economies (Stiglitz, 2002; Manzagoll, 2003). The mineral industry is recognized as being globalized because it satisfies the three aspects for the globalization of technology: global exploitation of technology, global technological collaboration and global generation of technology (Archibugi and Michie, 1995; Upstill and Hall, 2006).

The synchronism between the different parameters, and even between the different metal prices, is still not perfect. Therefore, several cyclic models have been proposed, either theoretical or based on the treatment of economic data (Cuddington and Jerett, 2008; Roberts, 2009; Passet, 2010). We follow hereafter the Heap model because it is based on the copper price, which is a good indicator of the economic situation and the second metal for exploration expenses after gold. Table 1 summarizes the major technical innovations for each period. A scientometric analysis was performed for the widely recognized leading journal on the subject of mineral deposits, *Economic Geology*, published since 1905, in order to decipher some key elements about the source of research in the field of mineral deposit geology. The detailed methodology is provided in the appendix.

First globalization

The first globalization event, or the Victorian era, arose mainly in the developed world after peace was established in America (Appomattox Treaty, 1865), in Japan (end of the Civil War, 1868) and in Europe (Frankfurt Treatise, 1871). It corresponds to the second industrial revolution or the neo-mercantile period (Chandler, 1990; Landes, 2003). Globalization arose mainly because of the high technological level of communications that allowed for the efficient conveyance of information (postal system, telephone, transatlantic wireless "TSF"...) and ore (development of bulkers: the first coal bulk carrier ship was built in 1852). It was a time of great international mobility, with 33 million people leaving Europe between 1870 and 1913, mainly to North America where immigration numbers peaked in the US in 1900. American urbanization increased from 23% in 1880 to 46% in 1910. At the end of the first globalization period, the US had replaced Great Britain as the leading power. However, such a shift of world power did not happen without numerous crises and bank defaults (Vienna 1973; Paris 1882; London 1890; New York 1893), and the end of the century was, as in 1929, known as the Great Depression. Severe crises took place, such as the silver crisis in 1891, which was initiated by the demonetization of silver in India to adopt the gold standard, with consequences all over the world, especially in Australia, America and Europe (Hoffmann, 1946).

Needs of the industry

The first globalization period corresponds to a widespread increase in the consumption of iron and coal, extracted mainly from Palaeozoic basins in Europe and Northeast America. It was also marked by a sharp rise in the consumption of base metals. The mineral industry had to respond to the considerable demands of industrialization, especially in the US and Europe, and 98% of the mineral consumption in these countries was locally fulfilled with very limited input from Third World countries, except for a few metals, particularly tin. This was also reinforced by protectionist policies in industrial countries, except the UK (Bairoch, 1994).

New metals emerged, such as nickel and aluminum. The nickel industry started with mining in New Caledonia (1874–1875) followed by the Sudbury basin discovery, c.

1889. Its growth was largely controlled by the military's demand for special steels, particularly for plating the American navy fleet during the Mexican war. The need for stainless steel and alloys also gave rise to the production of tungsten, chromium, vanadium and manganese. Production of aluminum rocketed from 75 metric tons in 1890 to more than 50,000 metric tons in 1912. Used first in jewelry as a semi-precious metal, aluminum's consumption boomed with the advent of new technological developments (planes, airships), opening up brand-new industrial sectors. The bronze industry also experienced a renewal, which boosted copper and tin consumption.

Others metals were also involved in this rapid market evolution. The invention of the tungsten filament for the light bulb in 1910 led to a sharp rise in its demand. In 1869, the opening of the Suez Canal reduced the delivery time of tin from Malaya to match the three-month delivery time for copper from Chile. This led to the establishment of the London Metal Exchange (LME) in 1876 and their institution of daily trading dates for up to three months forward. Between 1900 and 1914, the US became the leading copper producer, even ahead of Chile, the world's top mining country. In fact, in many countries, American mining equipment replaced the old British devices, especially Cornish machinery (Davey, 1996).

Organization of exploration

In order to respond to the rapid industrialization process, many new companies formed in all the mining countries, especially in the British Empire. Many of these groups were destined to become leaders of the twentieth century: BHP was formed in 1863, Rio Tinto in 1873, Peñarroya in 1881, Gold Fields in 1887, Asarco in 1899, Inco in 1902, Cominco in 1906 and Dome mines in 1910. Each of these companies developed world-class deposits and were very strongly associated with, or even directly owned by, international financial houses (Schodde and Hronsky, 2006). They were often managed by mining tycoons who left behind some epic tales (Dumett, 2008). In the French Empire and Belgium, public-private structures developed: the Katanga committee was in charge of mine development in the Copperbelt and controlled 20% of private companies; the Bureau Minier Chérifien in Morocco was the ancestor of the BRPM (presently the ONHYM) and had a minority participation in most mining projects.

For a long time, mineral exploration and mining was based on knowledge forged by German engineers; it was then transferred during the seventeenth century to Cornish specialists with subsequent spinoffs around the world. But this very practical knowledge was not enough to meet the challenges of the considerably more intensive exploration that followed. A first surge in mining schools occurred in the second half of the eighteenth century, mainly in Central Europe (Vienna, Selmec, Freiberg), France and Spain. A second surge coincided with the coal mining of the first half of the nineteenth century (St Étienne 1816; London 1851). The onset of the second industrial revolution led to a huge investment in knowledge in the training of highly qualified people in the field of precompetitive research for the mining industry. The Columbia School of Mines in New York City (1864) was the first major institution to develop this specialized domain in America and was followed by more than 20 universities all across America (Colorado 1874, Michigan 1885, Montana 1889...). In 1900, the University of California at Berkeley was the world's largest school of mines. Around the globe, new schools of mines were being built in other mining countries, such as Australia (Bendigo 1873; Perth 1902), Canada (Montréal 1871), Brazil (Ouro Preto 1876) and China where the China University of Mining and Technology was established in 1909 amid the late reign of the Qing Dynasty.

State involvement increased with the establishment of national and provincial geological surveys, mainly between 1835 (British Geological Survey) and 1896 (Geological Survey of Egypt) to take on the responsibility of mapping and target definition. The founding of the USGS in 1879 was the most ambitious scientific project of the nineteenth century. Although distinct from mineral exploration, research into extractive technologies had a major impact and was thus more internally controlled by mining companies.

The transfer of the central-European mining knowledge to the new world through the Cornwall minors was illustrated by the successive publication of textbooks on ore deposits, from the translation of the Von Cotta treatise in America (1870) to an explosion of books at the turn of the century (Phillips, 1884; Posepny, 1902). Key people moved to America, such as Waldemar Lindgren, a Swedish-born geologist trained in the Freiberg Mining Akademie (Hannington et al., 2000). The needs of the industry and the growing knowledge justified the establishment of a new domain-specific journal, *Economic Geology*, in 1905. USGS employees and American academics closely associated with the USGS founded the Society of Economic Geologists in 1920 (Skinner, 2005). The very first paper in the first volume of *Economic Geology* made explicit reference to German mining traditions (Ransome, 1905), but almost all the papers published in this journal were written by American scientists, and were typically single-author papers. In the US, ore deposit research was mainly done by the USGS and state geological surveys, and at major universities on the East Coast, such as MIT, Stanford, Harvard, Princeton and Yale (Figure 1). Two universities located near the booming iron mines of the Lake Superior region joined this distinguished group (Illinois and Minnesota). Several of the geologists were spending their summers working for private exploration companies, linking research to practical exploration (Lindgren, 1919). Major textbooks were produced, such as the 1913 tome by Louis de Launay, which coined the term *metallogeny*, and the Lindgren landmark textbook of the same year that formed the basis of mineral deposit classification for more than 50 years.

Target innovations

Table 1 and Figure 2 summarize the main mining discoveries of the first globalization period. Most of the major deposits were either rediscovered in old and sometimes archaeological excavations or discovered for the first time in surface outcrops by individual prospectors. Target innovations were mainly focused on iron, copper, nickel and gold. Experience gained in gold prospecting was transferred to other metals. The international mobility of the Cornwall minors led to the development of the numerous tin and gold mines throughout Australia in the 1870s.

Although copper had long been recognized in North and South America, the copper porphyry systems of the Andes and the Western US emerged as the most important new style of ore body (Bingham, Chiquicamata, San Rafael...). Such deposits greatly benefited from the sharp decrease in the cutoff grades for mining operations thanks to the mechanization of ore extraction and processing techniques, transferred from other segments of the industry (steam shovels at Messabi, bulk oil flotation in 1869 at Broken Hill). Although not fully understood at the time, porphyry systems clearly demonstrated a geological connection between copper and granite. The huge Copperbelt district also began to develop in Southern Africa (Roan Antelp, Ruwe and the opening of the Tsumeb mine 50 years after it was first discovered).

The Messabi Range (Minnesota) was the first large open pit excavation of banded iron formation ore (1892), and marked the shift of iron mines beyond the classic carbonate-hosted "minette" mines of the eighteenth century. It was also the place where E.J. Longyear sunk the first diamond drill hole in 1890.

Rich gold veins, both epithermal and orogenic, were discovered and formed the basis for several world-class districts, such as Kalgoorlie and Charters Towers in Australia, Homestake in Dakota and the Ontario segment of the Abitibi belt in Canada (the Dome Mine, Hollinger McIntyre and Kirkland Lake deposits). Like the flotation process for porphyry copper deposits, the cyanidation process, developed in New Zealand in 1887, was slowly introduced around the world and led to exceptional gold recoveries, such as from the Rand conglomerate in South Africa. The Rand was also the place where deep drilling programs demonstrated their importance in evaluating a deposit's mining potential.

Some of the deposits discovered as outcropping mineralized rock had specific characteristics not well understood to be of use as ore deposit models, such as the iron of Kiruna (Sweden), the lead of Broken Hill (Australia), or the copper of Flin Flon (Manitoba) and Outokumpu (Finland). New styles of deposits were mined due to the greatly diversified needs of the industry, the drastic rise in metal consumption and the expansion of the technological sector: aluminous bauxite in Southern France (Sallindres), nickel in New Caledonia and Canada (Sudbury), and manganese in Russia (Nikopol).

Technology-based innovations

Exploration techniques were based entirely on prospecting and field geology. Most of the deposits were developed in already known areas with outcropping ore. Some discoveries also occurred by chance during the emergence of new populated areas (diamonds in South Africa, Broken Hill in Australia). Several deposits were serendipitously discovered while trench digging during railway construction (Cobalt and Sudbury in Canada, Le

Chatelet in France...). Others were uncovered in areas considered barren at the time based on prevailing geological knowledge of the setting (gold in banded iron formations at Homestake, 1878). It was the golden age for mineralogists who were the only specialists of ore deposits, and the mapping of mineralogical zoning patterns around plutons was pioneered by Posepny (1902), De Launay (1913), Emmons (1918) and Lindgren (1922) (Figure 3). The understanding of supergene zoning around deposits (Emmons, 1917) was a key achievement for exploration in subtropical countries. The daughter of mineralogy, geochemistry was in its infancy, with the key works of Goldschmidt in Norway, Clarke in the US, and Vernadsky in Russia at the beginning of the century, immediately applied to mining exploration (Létolle, 1996).

The development of the airplane industry brought with it aerial photography, and considerable advancements were made in this field after 1919 for the purposes of oil exploration in the Middle East before being applied to the search for mineral deposits.

The development of deep (700-meter) diamond drilling in 1892 was instrumental to the discovery of the downward extension of the Witwatersrand gold deposits. The development of lightweight surveying equipment for geologists — such as the "Pocket Transit," a handheld surveying compass that could also measure horizontal angles, patented by Brunton in 1894 and manufactured by Ainsworth, a Denver watchmaker — were of invaluable assistance to geologists in the field. Early tests of geophysical methods in Russia and Sudbury (Canada) in 1901 by Thomas Edison's company showed that simple magnetism could be used to detect metallic mineral concentrations at depth (Laznicka, 2010).

Conclusion on the era

The Victorian era was the first large industrial global mining boom, supported by a colonial structure. For the first time, major financial and industrial groups were able to explore for ore all around the world. Companies were mainly opportunistic, employing prospectors and limited exploration organization. Almost all discoveries were made at the surface in outcrops of bedrock, without the need for indirect technologies. These discoveries laid the foundation for the mining industry of the twentieth century. It was also the beginning of a growing environmental sensibility: the term *conservation* was coined in the US by a forester, Gifford Pinchot, during President Roosevelt‘s administration (1901–09), and the first national parks were set up in the US, Canada and Australia. At the time, the world was still vast enough to support both environmental conservation and mining.

The 1918–1945 crisis

The end of the first globalization period was a diachronous process, with early catastrophic failure (the sinking of the Titanic, 1912), political breakdown (World War I, 1914–1918, the Soviet Revolution, 1917) and economic collapse (Black Friday, Wall Street, 1929). Tight restrictions on immigration were imposed in 1924 in the United States by the Johnson-Read Act. Although industrial demands surged as a result of World War I, particularly for the high-tech metals of the time (aluminum, nickel, tungsten…), the price of copper and most other metals lost ground between 1914 and 1933. Gold was left as a standard until 1933. Many mines closed due to the collapse of metal prices after the end of World War I. The metal demand would later rise again due to international rearmament before the World War II.

Needs of the industry

This period of crisis represented a decrease in growth on a worldwide basis. The demand for metals dropped significantly and prospectors turned toward the only metal with a rising value: gold. In 1934, the US increased the price of gold from $20.67 to $35.00 per ounce, leading to a boom in gold exploration, gold mine development (especially in northern Canada in the Yellowknife and Abitibi regions) and gold production.

Despite an exploration slowdown for other metals, several mines nonetheless managed to open thanks to the results of the earlier peak in exploration activity. But investments remained low and the diminished rate of discovery of new deposits was of increasing concern to the industry by the late 1930s and early 1940s. In Australia, this paucity of new discoveries, after the flood of the previous century, led some to believe there were few new resources to be found and the industry would gradually run down. An embargo was placed on the export of iron ore in 1938 by the Commonwealth Government, when reserves of high-grade ore were believed to be too low (McKay et al., 2000).

At the end of this period, World War II increased the demand for technological metals, such as aluminum and titanium, and led to the opening of new bauxite mines (Jamaica, Surinam...) and titanium black sands (Australia, 1941–1943). In 1942, the Brazilian federal government aggregated the Itabira mines and, one year later, the Vitoria-Minas Railroad into a public company under the banner of Companhia Vale do Rio Doce. By 1949, the CVRD was responsible for 80% of Brazilian iron ore exports. This signaled the increased involvement of state in mining that was to characterize the second globalization period.

In the 1920s and 1930s, many mining companies formed their own exploration departments, employing private geologists and prospectors. The distinction between prospecting, a geologic mineral exploration team and mining became clearer as companies invested more in drilling. Geological reasoning began to challenge surface prospecting as new deposits were discovered hidden underground. Joint projects between governments and companies led to the construction of public-private laboratories (Pattit et al., 2012), such as the Battelle laboratories in 1923, which focused on steel and zinc processing in the United States.

The same organization of exploration was occurring in the communist world. The Soviet revolution was based largely on economic development and necessitated the development of new ore deposits in the vast, almost untouched former Russian Empire. From 1922 to 1934, the Soviet Academy of Sciences organized more than 250 expeditions to study geology, geochemistry and mineralogy throughout the USSR. Some were remarkably fruitful: the giant Norilsk nickel district was discovered in 1918; the Kola magmatic phosphate deposits were discovered in 1923 and mined six years later. New Siberian districts were developed in Transbaikalia and the Far East, all belonging to state companies.

Target innovations

Ore deposit research was rather similar to that of the previous period. The research conducted by geological surveys and academics widened to include a broader range of deposit styles from all around the world, with new studies taking place in the southern part of the African continent and in South America.

In Africa, mining in South Africa migrated from gold-only resources to more industrial products such as copper. Moroccan phosphates were developed to answer the need for fertilizers. Several major districts discovered during the nineteenth century opened during or just after World War I, such as Climax for molybdenum (US; discovered in 1879 and mined from 1916), Sullivan for lead-zinc (Canada; discovered in 1892 and mined from 1920), Nsuta for manganese (Ghana, 1917) and the Zambian Copperbelt by the company Selection Thrust (1927). The Mount Isa copper-lead-zinc discovery in 1923 was quickly followed by mining in 1931. The Horne copper-gold deposit was discovered in 1926 by chance and entered into production the following year. The discovery of these major stratabound resources impacted the geologic understanding of the time, moving from a pure granitic intrusion-related vision to a better appreciation of the importance of lithological control.

Technology-based innovations

The rapid growth of chemical and physical research at the beginning of the century led to the development of numerous new applications in mineral exploration. For example, the Geiger-Muller counter was invented in 1928 and used to detect radioactive minerals; magnetic methods were instrumental in the discovery of West Witwatersrand gold; and the gravimetric method was tested. In 1930, the Society of Exploration Geophysicists was formed and a special journal, *Geophysics*, started publication in 1936. Computerization of geological information occurred as early as 1940 (Cady et Boley, 1940). The number of drilling programs increased, yielding some unexpected discoveries, such as the potash deposits of Esterhazy, Saskatchewan, in 1943 by an oil-drilling rig.

In Soviet territory, the pioneering work of Mendeleyev, Vernadskii and Vinogradov were developing the basis to understand the mobility of chemical elements in the Earth’s crust

(Bailes, 1990). Immediate applications followed, such as the Fersman apatite discoveries on the Kola Peninsula, one of many discoveries credited to Soviet expedition teams.

Conclusion on the era

It is a common assumption that wartime yields growth in the mining industry. The downturn of the economy from 1918 to 1945, marked by two World Wars, clearly shows that this is not the case. A lack of investment in knowledge and exploration, and the slowing rise in the consumption of metals, led to a period with few innovations in mining and mineral exploration. However, fundamental discoveries in physics, mainly in the Western world, and chemistry, mainly in the communist world (Goldschmidt, 1937; Suess, 1988), were preparing the ground for the revolution in the second part of the twentieth century in the new fields of geophysics and geochemistry.

Second globalization

The second globalization corresponds to the post-war reconstruction era, between 1945 and 1971–1975, especially in Europe and Japan. The economic growth was largely driven by the automotive industry, along with other consumer goods that relied on electricity. This created an enormous demand, not only for basic metals such as copper, iron and bauxite-aluminum, but also for rare metals such as platinum, chromium and titanium, which were needed mainly by industries involved in aeronautics, nuclear power, spatial exploration and electronics. Moreover, during the Korean crisis, from 1950 to 1957, the prices for many metals and exploration expenditures rose rapidly, especially in the former British colonies. A boom in commodity prices occurred from 1951 to 1953, peaking at the beginning of 1951 at 45% above 1949 values. It was the glory years (Snow and Juhas, 2002). But then the US recorded its first global deficit in 1971 and the oil crisis exploded in 1973.

Needs of the industry

World War II increased international awareness about the uneven distribution of mineral resources. Metal production partly shifted from domestic to international, notably in Japan and Europe; for example, copper imports to Western countries more than doubled from 21% in 1913 to 50% by 1970 (Bairoch, 1994). Bauxite mining began in Jamaica in

1943, and iron mines began operating in Australia and Mauritania at the beginning of the 1950s. After 1960, the growth and risk associated with large investments in foreign countries prompted ever-bigger mining operations. The process was helped by the development policy set up by the Paley Commission (1948) that demanded the organization of fairer trade. As a United Nations organization, the World Bank contributed significantly to the development of mining resources and partly to the prolongation of the colonial system after World War II. Currency changes were stabilized with the Bretton Wood Accord. But the artificial low price of gold, fixed at $35 per ounce, discouraged its exploration everywhere and resulted in a lower rate of new gold mines between 1945 and 1965.

A more widespread and increasingly popular environmental consciousness about the possible limits to growth through the depletion of resources developed in the 1970s (Meadows et al., 1972). That decade saw the emergence of environmental protection issues.

The end of this second cycle was marked by the petroleum crisis, the construction of mining cartels trying to regulate metal prices, and the degradation of the mining infrastructure in several developing countries, due largely to a lack of investment and competency.

Organization of exploration

The Cold War period was fundamentally rooted in Keynesian thinking, where the states had the ability to direct the economy and even substitute private sectors with national organizations. Immediately following the decolonization era, nationalizations became increasingly common after 1960, leading to the expropriation of several foreign companies (32 between 1960 and 1969), particularly in South America (Chile, Peru, Bolivia, Brazil, Venezuela), Africa (Zaire, Zambia, Guinea, Madagascar, Mauritania), India and Indonesia. The acquisition of mines and on-site processing facilities by the state ended the colonial monopoly.

Occidental countries reacted by stockpiling (US) and by cooperation (the European treatise on coal and steel, the prelude to the European Community). Large public or

Crown companies were developed and some met with significant success in their early years (Codelco in Chile, Gecamines in Zaire, Soquem in Québec). In Chile, the nationalization of copper was initiated in 1967 when the government took over 51% of the capital in Kennecott's El Teniente mine, achieving sole ownership in 1971. The involvement of local governments in the ownership of mining companies was facilitated by the global economic and political situation of the 1970s, marked by the success of OPEC and the Third World's demand for a new international order.

Before the war geology was sometimes considered a waste of time for most miners and geology companies alike; however, geology departments became organized in major companies after the 1950s, forming distinct divisions from the mining stream. A large part of the research was carried out by private laboratories, such as the Kennecott research center in Salt Lake City, Utah, for copper, the Peñarroya–Société Le Nickel in Trappes, France, and the Metalgeslschaft in Frankfurt, Germany, for base metals, or the CEA in Orsay, France, for uranium. Private-public associations were set up to solve specific questions. Geologists were organized into exploration departments assembling several specialties; discovery would require teamwork (Woodall, 1993).

The wall between the metals industry and the carbon-based energy industry of petroleum and coal became fuzzier, allowing some transfer of technological approaches from one side to the other. Metal companies bought coalmines and petroleum companies bought metal projects. The development of geophysics was directly related to this new organizational structure.

It was also a golden time for publicly funded geological organizations. Governments answered their fear of a Malthusian crisis (Meadows et al., 1972) by better managing their mineral resources and trying to secure the supply chain. In Québec, the SOQUEM crown company was developed in 1965. Most of the major geological surveys saw considerable expansion of their activities, requiring new structures and very often new decentralized laboratories away from the centers of capital cities. In 1968, the BRGM left its offices in Paris to move to Orléans. The U.S. Geological Survey's John Wesley Powell Building, in Reston, Virginia, was completed in 1973. Geologists from government surveys became the major producer of papers in *Economic Geology*. Several major ore deposit research laboratories, however, remained in the large universities.

The geography of metal production changed significantly. Due to the opening of vast unexplored regions and advances in communications technologies, Africa and South America were explored by Western government agencies and mining companies. The BRGM began mapping West Africa, and the USSR explored Northern Siberia. The United Nations were strongly involved in mineral exploration and contributed to several discoveries, especially in Latin America (Petaquilla, Los Pelombres).

Target innovations

Active exploration led to numerous discoveries of copper, nickel and iron. Detailed studies of mineral deposits in Europe and North America prompted a radical reinterpretation for several styles of base metal deposits, including volcanic-hosted massive sulfide and porphyry copper-molybdenum deposits.

Copper was actively explored in the Western US and led to the discovery and mining of the Pima and San Manuel Kalamazoo deposits. Mining using large open pits began in Butte in 1955, and after Lowell and Guilbert published a landmark paper in 1970 providing a better understanding of the model, several major porphyry-copper deposits were discovered around the Pacific, such as Ertsberg/Grasberg and OK Tedi in PNG, Petaquilla in Equator, and La Escondida in Chile.

A surge in mining discoveries occurred in Australia starting in the late 1940s, presumably related to the greatly improved knowledge of the country’s geology. This was due in large part to systematic geological and geophysical surveys conducted across the continent after the Bureau of Mineral Resources was established in 1946 (McKay et al., 2000).

Around the world, large stratiform deposits were developed: copper in the Zambian-Zairian Copperbelt, in Lubin (Poland), and in Udokan (USSR); uranium in sandstone (Colorado-style in the 1950s, and the beginning of the Athabasca and Kombolgie districts in the 1970s); iron ore (Liberia, Mauritania and West Australia); manganese ore (Grote

Eyland); bauxite; etc. Large volcanogenic massive sulfide deposits were discovered in Canada (Windy Cragy, Kid Creek), and sedimentary exhalative (sedex) deposits around the globe, from the Northern Territory in Australia (HYC: too fine grained to mine) to the Navan zinc deposit in Ireland. In 1962, John Livermoore and Alan Coope discovered submicroscopic gold in Carlin, Nevada, and Newmont set up the process to extract the yellow metal from this problematic ore (Morris, 2010). Discovered in 1966, the nickel Kambalda deposit was the result of exploration for VMS deposits. Additionally, at the close of this period, the exploration for stratiform copper deposits led to the discovery of the atypical Olympic Dam copper-gold-uranium deposit in South Australia (Woodall, 1994).

Sedimentary basins were also investigated with a new approach called *solution mining*. It originated in 1958 when a group of chemical producers, attending a Chlorine Institute meeting, discussed problems related to the production of salt brine. The meeting led to the formation of the Brine Cavity Research Group (BCRG) in 1959, consisting of 11 salt and chemical companies.

This period clearly marked the development of stratigraphy and sedimentology in mineral exploration, demonstrated by the strong association of these words in the citation indexes of the 1960s (Jébrak, 1997). With the development of so many mineral deposits hosted by sedimentary rocks, a group of European scientists countered the long-standing American-based plutonic tradition by coining the term *gitology* (Nicolini, 1990). Moreover, they formed the Society of Applied Geologists, and published a new journal called *Mineralium Deposita*.

The need for new metals was partly answered by the discovery of the platinum group element deposits in Stillwater, Montana, several niobium-tantalum pegmatite deposits at Tanco, Manitoba, rare earth elements at Mountain Pass in California, and titanium in both hard bedrock (Norway) and black sands (Australia).

Technology-based innovations

Fundamental geological breakthroughs, especially in structural geology and sedimentology, were instrumental in mineral discoveries during this period. Many new techniques were developed in geophysics and geochemistry.

As early as the 1930s, exploration geochemistry was being used in the Soviet Union territories (Sillitoe and Thompson, 2006), soon transferring to the Western world. Russian exploration teams, using highly structured lithogeochemistry-based exploration programs, were especially successful with the discovery of major massive sulfide deposits in Southern Oural and the giant Muruntau gold deposit in the Tien-Shan Mountains of present-day Uzbekistan (Jensen et al., 1983; Krason, 1984). Early Western applications in the 1960s were for porphyry systems (Meyer and Hemley, 1967) and the exploration of Cyprus-type massive sulfide deposits (Govett, 2009). Exploration geochemistry rapidly expanded to include soils, then stream-sediments, and quickly increased its detection capacity (Cloos, 1997). Techniques were later adapted for buried lateritic areas (Australia) and the subarctic environment (Canada). Microprobe analysis began in the 1960s with Castaing's first instrument, and quickly revolutionized our knowledge of mineral compositions. Fluid inclusion technology, another Russian breakthrough (N.P. Yermakov), revealed the composition of hydrothermal fluids responsible for transporting metals. It was exported to Europe and North America by G. Deicha and E. Roedder, respectively (Roedder, 1984), although this advancement in fundamental knowledge was seldom transformed into an exploration tool outside the USSR.

Early developments in computer technology were used to advantage in the field of ore deposit geochemistry (Helgeson, 1970), but this fundamental research and theoretical models still needed to be transformed into usable tools in order to be applied by explorationists.

The explosion of the motor vehicle industry had a significant impact on the mining sector. Mining operations began to convert from rail to truck, and the first trucks specifically designed for geophysical surveys were developed. In recognition of this novel approach, the name of the Mobrun copper-zinc deposit in the Abitibi greenstone belt of Québec is derived from its motor-driven geophysical discovery method: MOBile Run UNit.

Airborne geophysics really began after World War II, with the first electromagnetic survey using a wooden airplane (1948). The INPUT geophysical method was developed in 1959 and VLF in 1964. By the 1970s, the development of airborne geophysics had produced a peak in the discovery rate all around the world, especially in Canada (Lulin, 1990). The success was phenomenal, and one out of every ten anomalies was significant during those first surveys. Ground radiometry was proving successful on a worldwide basis in the discovery of major uranium districts.

Nonetheless, it was usually a combination of methodologies that led to finding a deposit. Specializations in exploration geology emerged quickly, and in 1970, the Association of Applied Geochemists was formed. Large corporations were able to develop pioneering techniques; for example, using computers to calculate reserve estimates and discovery probabilities (Bailly, 1984).

Increased production demands made it necessary to upgrade the ores before processing them into metal products. The strong growth of copper and bauxite production after World War II was the result of scaling up equipment and plants rather than the conception of new technical processes, and increasingly lower-grade ores could be mined during this period (Mudd, 2010).

Conclusions on the era

Framed by Keynesian concepts and driven by increasing consumption in the Western world, the second globalization was marked by a surge in the production of base metals, iron and aluminum, and many specialized metals for the emerging high-tech industry. The answers from the exploration industry were threefold: (1) renewed organization of exploration, with strong ties to public organizations; (2) a disruptive target innovation approach, and more geology-based exploration, opening up more sedimentary environments to discover a wide array of metals; and (3) development of indirect methods, especially in geochemistry and geophysics, to detect, for the first time, mineral deposits up to 50 m below the surface.

The 1973–2000 crisis

A new period emerged in 1973 with the arrival of the oil crisis — an attempt by resource-rich developing countries to gain more power on a global basis. It could be interpreted as the logical consequence of the decolonization that progressively developed during the previous period. The Third World began to emerge in 1954, starting with Bandoeng, Indonesia, and slowly became a political and economic force; the last colonial empires vanished, the Vietnam War weakened the role of the US, and several political scenarios led to inefficiency and corruption. Thirty-two expropriations occurred between 1960 and 1969 in Chile, Peru, Zaire, Zambia and Guinea, particularly for copper and aluminum. Other expropriations occurred between 1970 and 1976, especially for iron (Mauritania, Brazil, India, Venezuela and Chile), phosphates (Morocco) and tin (Bolivia, Indonesia). Most of the mining production in Africa decreased, except in Morocco and South Africa.

Two oil crises slowed down the growth in developed countries, reducing metal consumption, leading to an oversupply and triggering a widespread drop in metal prices, especially iron. The Bretton-Wood system ended with the liberation of the gold price in US dollars. A decoupling occurred between unit capital costs and the prices of most mineral commodities. Metal and mineral supplies were affected by labor disputes in mining areas, as well as political unrest in the metal-producing economies, especially in the Caribbean and African worlds. The emergence of environmental and Aboriginal issues added costs and uncertainty to the exploration industry around the Pacific. A major recession affected the world economies in the early 1990s, and industries from the first globalization were particularly affected, such as coal, textiles and metallurgy (Beaud, 2010). This led to increasing supply constraints on the metals and mineral sectors, prompting metal prices to rise (Farooki, 2009). The collapse of the Soviet Union in 1991 was soon followed by a lower demand for iron. Growth was still present in “tiger” countries, but these economies were small and only had a minor impact on the mining sector.

After 1990, the state-controlled mining industry had demonstrated, in most countries, its inability to produce both minerals and value. This was particularly evident in former communist countries and in developing African countries. In Quebec, the Soquem crown company was almost completely privatized to form Cambior Inc. in 1985. In France, the BRGM mining assets are also privatized in 1994. Market-based mineral development became almost universally accepted as the norm, and the World Bank promoted significant changes to the mining codes of many countries (Campbell, 2010).

The profitability (average return on equity) of the mining industry dropped almost continuously from 30% in 1979 to 2% in 1993 (Commodities Research Unit, London). The crisis delayed the implementation of many mining projects, except those for aluminum and uranium, which were increasingly in demand. Most metals during the 1980s and 1990s saw depressed prices, which led to inadequate investment in mining and processing, and little capacity was built into the system. The number of workers in the mining industry declined substantially due to both an increase in productivity and a reduction in demand. In just 15 years, from 1970 to 1985, 70% of the mining workforce was lost in the US (Tilton, 2001).

The pressures on profit factors forced small mines to close and increased the scale of production at the larger operations. The daily mill capacity at conventional copper mines, for example, rose by 352% (Crowson, 2006). The total number of mines decreased around the world, especially in Europe and America, where environmental pressures were mounting. The lack of funding also led to stronger vertical integration in the mining industry, most notably concerning the processing of bauxite to alumina and aluminum, and establishing new industrial conglomerates, averaging out the risk on different commodities.

The only area of the sector that remained active during these years was gold, considered as a safe haven against the crisis.

Needs of the industry

The automobile industry remained the biggest consumer of metals, with a peak in the 1990s. In developed countries (US, the European Union, Japan), mature industries progressively faded out due to the shift toward a tertiary-based economy. At the beginning of the period, the demand for copper rose in response to the expansion of electrical and communication networks. In France, the *Plan Cuivre* ("Copper Plan") subsidized copper exploration, resulting in the discovery of the major Neves-Corvo deposit in Portugal. Ironically, when this deposit was discovered, the French government was tempted by fiberglass technology and sold the giant deposit to a British mining conglomerate.

The low price of metals reduced the real return on capital for operating mining companies worldwide. Although the demand for gold was not directly related to economic infrastructure, it doubled between 1977 (1,600 t) and 2003 (2,985 t), mainly due to the rise of Asian economies. The Chernobyl accident in 1986 triggered a decline in the demand for the nuclear industry. To strengthen their assets in a recession world, major mining groups diversified their production and tried to build conglomerates. Industry was progressively transferred to developing countries, especially those in Asia. As a result, the diversity of metal needs rose in tandem with the growth of the information technology industry.

Beginning around 1980, the discovery timeframe changed in response to the increasing influence of the financial markets and their search for fast returns on investment. The mining cycle had to shorten, particularly in the gold industry, and even the usual ten years from discovery to mining was thought of as being much too long.

At the end of this period, the general feeling among exploration geologists was that the world was going to suffer a prolonged mining recession (Snow and Juhas, 2002). This turned out to be largely untrue because their vision of the world was limited to traditional developed countries and did not include the upcoming exceptional rise of China and India, two countries situated well below the radar at the time.

Organization of exploration

The rebirth of the entrepreneurship approach and the externalization of mining operations answered the new challenges posed by this period of recession in the mining sector (Frost, 1980). It resulted in the creation of the junior company system, particularly in

Canada. Combined with a reduction of state involvement in greenfield exploration, junior mining companies occupied an increasingly prominent position in the early phase of exploration and development, draining more risk-venture capital (Figure 4). The number of small mining companies grew continuously from 1934 to 1970, and only showed a slight decline during the crisis. However, regulatory and legislative changes triggered a sharp rise in the number of companies during the 1980s, up to almost 2,900, before dropping off again until the end of the century (Russell et al., 2010). The junior company system was well suited for the popular precious metals sector during this period; in fact, a small gold exploration company could develop a deposit itself with only a limited amount of investment. In more specialized domains, such as uranium and diamond, junior companies seldom had the technical and financial capacity to develop a mine alone, and market knowledge was so important for industrial minerals that few explorationists could transition to production.

The decrease in commodity prices between 1973 and 2000 reflected the end of the decolonization process, and the rise of sovereign equatorial countries had a major influence on the structure of the innovation chain in Western countries. On one hand, it was demonstrated that state-managed agencies did not have the necessary organizational, human or financial resources for mining development. This was especially true in a doldrums period following a peak in metal prices in 1986 (Duke, 2010). Several fiascos occurred, and major public-driven mineral discoveries had to be sold to private interests. Geological surveys downsized; in the US this meant a reduction in the USGS workforce and closure of the Bureau of Mines (Rossbacher, 1996), and in France the BRGM privatized some of its activities. The role of the state as a producer of mineral products was phased out in developed countries. In an effort to promote more investment in developing countries, the World Bank guided the liberalization of African mining regimes during the 1980s and 1990s through the strong retrenchment of state authority (Campbell, 2010). On the other hand, the lower payback to companies reduced their capacity for proprietary innovation in exploration. Innovation no longer trickled down from the big companies. By the end of the period, most of the national companies had been privatized and most of the national surveys had reduced their mineral resource activities. Their role was partly replaced by work in universities, junior mining exploration companies and specific funding agencies. In less-developed countries, such as Chile, political actions led to nationalization.

In developed countries, this period was also marked by a strong decline in the academic world (Rossbacher, 1996). The University of Paris progressively lost its influence, and universities in Orléans and Nancy took over the management of ore deposit research. In England, the number of mining institutions decreased sharply, and the Royal School of Mines closed its undergraduate program. In the US, the Colorado School of Mines suffered a 15% decrease in student enrolment, whereas in Australia, mining programs were transferred to peripheral universities such as Brisbane, Perth and Hobart. However, with the increasing cost of research, the reorganization of the industry and the worldwide reduction in state involvement, most of the research previously done by the private sector and governments in the field of metallogeny was transferred to the few university centers dealing with exploration geology. In the largest centers, industry leaders helped define research programs through the establishment of industry-university consortiums with the help of public money: AMIRA in Australia (founded in 1959) was a pioneering success, and Canada followed later with CAMIRO in British Colombia (1995), MERC in Ontario (1997), CONSOREM in Québec (2001) and CMIC at a national level in 2008 (Lane et al., 2008). This situation typically corresponds to a field for which the level and organization of knowledge is already mature (Grandstrand et al., 1992) and where it has been demonstrated that proximity allows for a better transfer of knowledge (Kliknaite, 2009).

Target innovations

The very foundation of geological understanding was revolutionized by the advent of the plate tectonic paradigm (Sawkins, 1984). Although it would take years to integrate mineral deposits into the newly defined geodynamic environments, the concept allowed explorationists to follow mineral belts across oceans and relate the formation of mineral deposits to the evolutionary history of their host rocks. The discovery in 1979 of active “black smokers” — hydrothermal springs on the ocean floor — revealed a dramatic process occurring along mid-ocean rifts that was immediately extrapolated to ancient volcanogenic massive sulfide deposits, beginning mainly with the Cyprus ophiolite

(Parmentier and Spooner, 1978) and soon applied to the sedimentary-exhalative environment (Large, 1980).

Economic Geology's *75th Anniversary Volume* (Skinner, 1981) did not contain separate chapters for such important deposits as epithermal invisible gold, auriferous shear zones (orogenic gold), diamonds, hydrothermal platinum group elements, unconformity-type uranium, tantalum pegmatites or iron oxide-copper-gold. But several major discoveries stimulated more research on these types of deposits, even though academic funding remained generally low in most countries.

The number of discoveries dropped sharply between 1970 and 1986, from more than 30 per year in the base metal sector to less than 5 (Goodyear, 2006). The most notable discoveries were major unconformity-type uranium deposits in Canada's Athabasca Basin (Cigar Lake in 1981 and Mac Arthur in 1988), sedex-type deposits (Red Dog in Alaska, 1989), epithermal deposits (Yannacotcha in Peru, 1991), diamonds in Australia and Canada (Argyle in 1979 and Ekati in 1998), and iron-oxide Cu-Au-U deposits beginning with the Olympic Dam saga and followed by other important discoveries in Australia as well as Brazil and Chile (Salobo in 1977; La Candelaria in 1987; Ernest Henry in 1991). A direct result was the definition of new deposit types, such as unconformity-type uranium (Hoeve and Sibbald, 1978), diamondiferous kimberlites (Haggerty, 1986) and IOCG (Hitzman et al., 1992). Advancements in computer technology made it possible to streamline ore deposit classification. The Deposit Modeling Program, supported by the IUGS and UNESCO (Cox and Singer, 1986; Kirkham et al., 1993), popularized the North American approach and eventually squeezed out Soviet concepts.

The development of isotopic geochemistry began to solve one of the biggest challenges in ore deposit geology: the age of the deposit. To this day, it continues to be among the key fundamental approaches in metallogeny for understanding the geological setting of deposits and identifying potential new districts, although its application in mineral exploration remains underdeveloped.

Similar to the 1918–1945 crisis, gold retained its good value during the 1973–2000 period, and mining exploration was active in stable countries such as Australia and Canada. By the end of the 1980s, detailed studies deciphered the relationship between the seismic cycle and lode gold mineralization, integrating all such deposits in a rather embracing concept of orogenic lode gold deposits, which remained almost undisputed until the end of the period (Groves, 1993; Groves et al., 1998).

Technology-based innovations

With the introduction of the first microprocessor in 1975 and personal computing in the following years, the age of digitized information reached all areas of the earth sciences. Mineral exploration was at the forefront of developing computerized applications, with the first use of an expert system to predict the location of mineral deposits (Prospector: Campbell et al., 1982). The digitalization of information combined with the tremendous augmentation in data-processing capacity (Moore's Law) transformed every type of mineral exploration activity. The first spreadsheet and word processor appeared in 1979 and were immediately used by explorationists. Database development began in 1985 and greatly improved the organization of the rapidly growing amount of exploration and mining data.

The progressive introduction of computer chips in all kinds of technologies led to a size reduction in equipment coupled with larger and accelerated capacities. Geochemistry also entered a new era with the development of multi-element analysis at the parts-per-million level (Kamber, 2009), all electronically controlled, and the increase in both analytical accuracy and speed was particularly important for large-volume geochemical surveys. In addition, statistical treatments and geographical representations opened up new fields of expertise for exploration geochemists. Geophysics also benefited enormously, with the development of several variants of earlier techniques, which increased the depth of penetration by using more and more channels. Miniaturization and computer power also allowed geophysicists to perform down-hole surveys and sophisticated data processing. Computerized automation reduced operating costs by economy of scale.

The space sciences reached maturity with the development of several major applications, including telecommunications and remote sensing. The launch of the first Landsat (ERTS) satellite in 1972 opened a new era of Earth observations, and remote sensing progressively became a commercial market filled with suppliers and service companies.

Technological development played a major role in ore processing, such as the development of the carbon-in-pulp method to recover fine-grained gold from low-grade ore in Nevada and Australia. Both heap and pressure leaching reduced the coast of treatment (McNulty, 1998). It was a different story for copper, with limited demand and increasing production costs (especially due to rising energy prices), resulting in a crisis in the 1980s in both Chile and the US. More than half of the copper mines in the US closed (Tilton, 2001), and the survivors resisted because of a strong growth in productivity (doubling from 1980 to 1986), notably by the adoption of the leach-solvent extraction-electrowinning process (SX-EW) to produce copper cathodes. Productivity also increased in Chile, but a little later (in the 1990s), and because of mining larger porphyry copper deposits (Seedorff et al., 2005).

Conclusions on the era

The 1973–2000 period was marked by low metal prices and a marked reduction in mining company activity. Paradoxically, it was also a time of great innovation; after all, "*necessity is the mother of invention*." Low metal prices required productivity to improve, a challenge that was achieved by reorganizing the innovation chain, increasing the average size of mineable deposits and lowering mining costs, particularly in developing countries. In the developed countries, automated processes and a reduction in manpower kept production prices below the market price.

The rapid transfer of many innovations from the electronics and space industries to the mining industry also contributed greatly to speeding up the system as a whole, and had a considerable impact in the fields of geophysics and geochemistry. In mineral exploration, the revolution of plate tectonics offered a completely renewed vision of geology, and several new styles of ore deposits were recognized following the discovery of some exceptional deposits.

Third globalization

Like the second globalization, the third period emerged after relative peace was re-established, this time marked by the end of the Cold War. It was shaped by a revolution in communication technologies (the Internet) and the arrival of a new group of consumers. In contrast with the first two globalizations, the rise in urbanization was largely the result of internal migrations (mainly within China) and not international immigration. The demand for metals rocketed in response to an increased involvement of the BRIC states, especially China, in the world economy (Maddison, 2001). Foreign direct investment in China tripled in one year (1993) and continued to grow under the leadership of Prime Minister Zhu Rongji from 1994 to 2003. China's economic growth was marked by an average annual GDP growth of 10% from 1990 to 2007, climbing to 12% per year in 2006 and 2007. The rapid urbanization of Chinese society required ever-greater quantities of mineral commodities to build infrastructure and supply construction. Therefore, growth was driven by the industrial sector, which accounted for 48% of the value-added GDP in 2006.

Needs of the industry

The entire metal market was concerned by the surge in metal prices. On the one hand, China and other developing countries needed significant amounts of iron and base metals. For instance, the annual per capita consumption of copper increased from 485 grams in 1990 to 4,434 grams in 2010, and per capita steel consumption rose from 46.7 kilograms in 1990 to 432 kilograms in 2010 (compiled from USGS data). The price of base metals rose sharply, reversing an almost century-old tendency (with the exception of the post-World War II rebound).

On the other hand, metal needs became highly diversified due to the development of new industrial segments, such as the generation of electricity, transportation and energy storage (Eggert et al., 2008; Tiess, 2010). A revival of the nuclear industry occurred in response to reduced carbon footprints — in spite of local disasters and green party activists — and required new supplies of uranium in addition to boron, zirconium, barium, hafnium and cobalt. The aerospace industry needed new metals, such as rhenium and niobium, as well as more of the traditional metals, such as nickel, aluminum and chromium. The production of electricity from wind turbines triggered strong growth in the demand for permanent magnets, which use rare earth metals (praseodymium, neodymium, samarium), and the transport of this power required large quantities of classic metals (aluminum, iron, manganese, chromium, nickel, copper), and less abundant products (carbon, vanadium, gallium, indium, cobalt, molybdenum). Photovoltaic production required selenium, tellurium and silicon, and even precious metals were needed for connectors (gold, silver) and catalysis (palladium, platinum). Energy storage metals included lanthanum, lead, tantalum, manganese, cobalt, nickel and lithium (Bihoux and De Guillebon, 2010), the latter of which also became a key component of the car industry. Most of these new energy-related technologies require greater amounts of metals per kilowatt than traditional non-renewable energy sources such as petroleum or coal. Up to 45 elements were considered of interest by the metal industry during this period, up from only ten during the first globalization (Eggert et al., 2008).

After the lows of 2000, the price of many metals rose dramatically, with most commodities doubling. This surge may have been related to the low yield of new discoveries from the exploration sector toward the end of the previous period, which inevitably led to a reduction in the number of producers, as well as the intense demand from developing countries. The result was that low-grade halos around most deposits became economic and new mining targets could be developed.

Organization of exploration

The comeback of metal prices helped super-major mining giants to rise and hold large cash positions. Consolidation first occurred in sectors within the industry — base metals (BHP-Billiton, Rio Tinto), aluminum (Alcoa, Alcan), iron (Arcelor-Mittal) and gold — then reached an intersectoral level that led to the construction of oligopolistic super-majors, similar in size to those in the oil production industry. This increase in company sizes correlated with the increasing size and economic role of “world-class deposits” on the global production scene (Schodde and Hronsky, 2006). Moreover, the integration of the value chain allowed for economies of scale. The key element was the expansion of the old Third World mining companies: Grupo Mexico took over the old (first globalization) lead-zinc industry in the US, India’s Mittal bought the consolidated

European iron industry, Russia’s UC-Russial/Norilsk bought the platinum group element industry in the US, Brazil’s Vale became one of the leading super-majors by absorbing Inco and state-controlled Chinese groups bought mines all over the world. Two families of super-majors emerged, one inherited from the first globalization, mainly based in the former British Empire, and another brand-new family, mainly based in the BRIC countries, illustrating the driving power of the consumer market. Some public remnant companies resisted, however, such as Codelco in Chile. Such consolidation could have been a significant factor for the decline in the amount spent on technological innovations (Filippou and King, 2011).

The organization of exploration was also affected by structural changes in the mining chain (Figure 4) (McDonald, 1998). At the beginning of the twenty-first century, only a few private research centers remained in the world, and they dealt with very specific styles of deposits, such as diamonds (De Beers) and lateritic nickel (SLN-Eramet). Vale opened a new center in Brazil. As a reflection on the changing role of the state with its weaker financial capacity, and the new political and economic equilibrium of the world, some countries such as Japan decided to close their geological survey and replace it by a more comprehensive agency (e.g., JOGMEG), fully in charge of the supply and management of metals (2004). Several governments supported a new phase of regional surveys to stimulate the private exploration sector and renew the stock of exploration projects. A new investing effort was supported by governments in order to develop world-class research and tertiary education. In Australia, basic research accounted for 40% of government R&D; for example, new groups such as CSIRO (the national research laboratory), several Cooperative Research Centres (CRCs) and university-based centers of excellence were formed and thrived in collaboration with Geoscience Australia, which supplies geo-scientific information for government and industry (Upstill and Hall, 2006). Although more than one hundred countries have rewritten their mining laws since 1985 (Campbell, 2010), some new changes were still needed to create a more favorable distribution of mining income amongst communities, governments and companies.

For the first time since the late 1980s, junior companies emerged as preeminent players on the mining exploration scene, beginning with gold. They represented a multi-divisional form of mining exploration companies with better risk management, being limited to small entities that allowed a simpler diversification strategy into targets (products) and technologies (Chandler, 1990). As the price of gold flattened in the early 1990s, the juniors diversified and took advantage of the high prices for base metals and diamonds until 1997 (World Banks and IFC, 2003). The entire junior sector suffered from several crises, notably the Bre-X scandal in 1997, the subsequent diversion of investment into the technology boom, and the profound depression of metal prices in 1999 and 2000 (Hall and Redwood, 2006). A strategic distinction emerged among developed countries, splitting resource-rich countries such as Canada and Australia from already exploration-mature parts of the world, such as Europe and the Eastern US. Several junior company models materialized, from service-intensive to mining-oriented. Most seemed to be more innovative than the majors, with a strong tendency for diversification, especially in target definition (Laznicka, 2010).

On the technology side, more companies outsourced their activities, generating considerable growth in the number of technical service companies. This was the case in Australia where, after long-term research and innovation policies that focused on constructing critical masses and a supply of heavy scientific equipment, several exploration and mining service companies became very successful, especially in geophysics. The same strategy of concentration was developed in Ontario, around the Sudbury network, and in Johannesburg, South Africa. Major companies adopted open-source innovations as a new strategy, following the Goldcorp initiative in 2001 (Tapscott and Williams, 2006). In 2007, Barrick Gold turned to the Internet to solicit ideas, in an auction-style approach, on how to recover silver from a silver-gold deposit in Northern Argentina.

Target innovations

The third globalization is a recent event and the fruits of the renewal in exploration are still not fully recognized. In most traditional exploration areas (for example, the Abitibi, Carlin, Witwatersrand, Yilgarn and Cloncurry districts), surface deposits became increasingly difficult to find, and the first 300 meters show signs of exhaustion. However, better indirect methods of detection, an improved geological understanding, lower drilling costs and deeper mining methods allowed deeply buried classical deposits in established districts to be developed, such as VMS (La Ronde, Canada, down to 3,000 m below surface) and porphyries (Ridgway, New South Wales, down to 500 m; Resolution, Nevada, down to 1,300 m). The rise in metal prices, the higher cost of energy and a better understanding of the permeability of the Earth's crust allowed more in-situ leaching (ISL) mines to develop, such as those for uranium in Kazakhstan.

Exploration began in several new regions, such as Siberia, Eastern China, Mongolia and some parts of Africa. Several large deposits were discovered, especially along the paleo-Tethys structure from the Mediterranean Sea to the eastern part of the Eurasian continent, such as Oyu Tolgoi (Mongolia), Reko Diq (Pakistan) and Xietongmen (China). The Soviets' growing understanding of several Siberian deposits had not yet been integrated into American mineral deposit standards (Seltmann et al., 2010).

The new discoveries, especially those containing metals of the green economy, prompted the definition of new metallogenic models (Goodfellow, 2007). For example, intrusion-related metallogenic systems became better understood when mineralization associated with reduced granites (intrusion-related gold) was mined (Lang and Baker, 2001), a better definition of IOCG deposits was developed (Groves et al., 2010), and molybdenum and rhenium were discovered in black shales near intrusive bodies (Merlin: Brown et al., 2010). After a decade of consensus, the orogenic gold deposit model began to crumble following the discovery of early gold hosted by turbiditic foliated black shale and new insights into the role of magmatism at the end of Archean times (Duuring et al., 2007).

Technology-based innovations

Since the advent of geochemistry and geophysics following World War II, discoveries of subsurface deposits in well-explored countries have become increasingly common and surface discoveries increasingly rare. By the year 2000, only half the discoveries in Australia were buried under less than 15 meters of cover, with 40% found between 15 and 200 meters below the surface, and the remaining 10% even deeper (Australian Academy of Science, 2010).

The information revolution continued to infiltrate all technologies. In 2010, the most cited innovations were technical (Jébrak, 2011). The increased use of GPS in the field and ICP-MS analyses in the laboratory both increased the quality and speed of data acquisition. The large analytical spectrum of the ICP-MS technique was directly responsible for the discovery of a new rhenium deposit (Brown et al., 2010). Other cited innovations in exploration technology were developments in lithogeochemistry, exploration mineralogy (indicator minerals for diamond, sedex and porphyry deposits), the use of portable sensors, and the improvement of electromagnetic techniques (Tempest) and airborne gravimetry. Portable mineralogical and geochemical analyzers were products of the miniaturization trend in electronic components, and increasingly efficient software, combined with GPS devices, accelerated the acquisition of data in the field. Drilling technology evolved slowly, with the transfer of the petroleum industry's large-diameter core to the traditionally smaller-diameter domain of mineral exploration, along with the use of orientated drilling to reach deeper targets and down-hole analysis.

Explorationists also benefited greatly from the increase in computational power, larger data-management capacities, 2D and 3D integration, and new inversion software (Upstill and Hall, 2006). Australia developed numerous computer applications for mining and supplied 60–70% of mining software worldwide. The Internet became the dominant means for information access and communication.

The e-staking developed by the Québec government was also cited as a huge and positive technology change that led to significant changes in the organization of exploration programs, greatly speeding up the staking process (Jébrak, 2011).

If we extend the current technical trend in mining exploration and account for the advancement of applied research, a number of incremental innovations will likely affect the way we work in the near future. The information technology era is largely based on the miniaturization of components, the development of micro- and nano-sensors with larger bandwidths, and an increased capacity for accessing and processing data.

Moreover, it has been observed that technology is presently transferring from home to business. Although not widely used at present, the electronic field book is an expected future development, providing better on-site data acquisition, analysis and interpretation (position, image, mineralogy, geophysical parameters, geochemistry), as is the transfer of petroleum industry-style logging to the mining industry and additional developments in down-hole geophysics and 3D modeling, to name but a few.

Conclusions on the era

The third globalization event is not yet finished, thus conclusions are premature. As was seen during the first globalization event, accelerated growth in the demand for mineral resources and power shifts at the international level could not have occurred without serious adaptation crises that momentarily appeared capable of limiting or even stopping the growth. The new international distribution of work includes funding by Chinese groups, innovations and exploration by companies, particularly juniors from Western countries (Australia, Canada, Europe), and the presence of giant mines in remote locations at the edge of civilization where social responsibility is often considered limited. This distribution will change with China’s eventual (albeit likely gradual) legislative changes and greater social awareness concerning the need for long-term human and environmental management by mining groups.

DISCUSSION

Three questions arise from this overview of innovation in mineral exploration and mining. What was the relative role of continuous improvement or incremental innovation versus disruptive innovation over the course of a century? Do the rates and types of innovation depend on the globalizations process? Is there any specificity in the exploration and mining innovation system?

Disruptive and incremental innovations

The evolution of the mineral exploration industry has been marked by both incremental and radical innovations that have profoundly affected the way people work and even the structure of the industry.

Incremental innovations correspond to improvements in cost or features for existing products, services or processes. They usually expand on existing technologies, with a linear and continuous trajectory. It is the equivalent to the “normal science” of Kuhn (1962). Disruptive or radical innovations represent the development of new businesses, product categories, platforms for successive developments, and/or processes that transform the economies of a business. They depend on the emergence of new technologies or markets, and are mostly sporadic and discontinuous.

The classification of innovations based on their origins (Abernathy and Clark, 1985) distinguishes between non-disruptive innovations (incremental innovations), market-disruptive, technology non-disruptive innovations organizational innovations), market non-disruptive, technology-disruptive innovations (revolutionary innovations), and both market- and technology-disruptive innovations (structural innovations). Figure 5 compares some incremental and disruptive innovations in mining exploration.

In target innovations, the disruptive events are clearly related to the need for new metals, the development of new extraction processes, the unexpected discovery of new styles of mineralization, metal prices (lower mineable ore grades) and the opening of new territories (Lulin, 2010; West, 2011). The need for new metals clearly results in structural innovations by creating new supply chains and the definition of new ore deposit models. Examples from the first globalization were iron, copper and gold. The recognition of the enormous iron potential of the Lake Superior area and the possibility of low-grade copper deposits associated with porphyritic intrusions answered the demand, and the huge capital they required caused a structural change in the mining industry and the establishment of mining giants, the legacy of which is still evident to this day. Uranium played a similar role during the second globalization, but due to its political significance and within the context of a Keynesian economy, the uranium mining industry remains mostly isolated and largely state-dependent. The control of twenty-first-century strategic metals (rare earths, lithium) has not yet reached a mature stage, but several new styles of deposits are emerging (rhenium-enriched black shales, rare earth-enriched IOCG, etc.). The development of new extraction processes has been equally disruptive, allowing new styles of deposit to be mined, whereas classic mining technology was mainly focused on high-grade sulfides, and the development of new chemical and physical techniques (cyanide, flotation) rendered non-traditional resources economic.

However, most of the major target innovations resulted from the unexpected discovery of deposits, rarely by the direct prospecting methods of exploration’s early days (the exception being Voisey Bay), instead almost always by indirect geophysical or geochemical methods: disseminated gold (Carlin), IOCG (Olympic Dam), komatiite nickel-sulfide (Kambalda), unconformity uranium (Rabbit Lake) and calcrete uranium (Yerillee). Therefore, serendipity has played a key role in target innovations. Empirical models were first developed in the short term and used as a strategic asset by the mining company that owned the knowledge. Although used in some greenfield exploration programs, most genetic models did not reach a mature-enough level to demonstrate their absolute necessity.

Rising metal prices resulted in lower cut-off grades for production, allowing new targets to be explored and new methodologies to be developed. The best examples are the development of porphyry copper deposits during the first globalization event, the rise of uranium and sedex-zinc deposits during the second and the importance of low-grade intrusion-related gold systems in the third (Hart, 2005). The opening of new territories allowed new styles of deposit to be recognized. At the end of the twenty-first century, the era of tropical colonization was followed by the recognition of the potential of supergene aluminum, manganese and nickel deposits. And once the former Soviet empire opened up, the exploration of the Tien Shan gold belts led to the discovery and development of a whole family of gold targets (Muruntau, Kumtor, etc.) associated with the specific Palaeozoic evolution of this continental margin. As yet unclassified deposits have been discovered in Canada, such as Eleonore (Jébrak and Marcoux, 2008) using a government financial incentive to explore vast Northern lands. However, several target innovations also arose in well-known districts through the unforeseen re-orientation of a deposit from the original substance of interest to another, such as the shift from iron to rare earths at Bayan Obo in Inner Mongolia, bauxite to gold at Boddington in Western Australia, iron to fluorite at Escaro in France, and the addition of gold and platinum group elements to iron at Itabira in Brazil. These examples once again illustrate the importance of serendipity in mining.

In technology-based innovation, disruptive events usually come from developments in other domains. It was the development of fundamental knowledge in physics, chemistry and mathematics that allowed the applied sciences (including the earth sciences) to be set up, and mining exploration often leapt forward after military (G2) and information age developments (G3) (Anon., 2011). This is related to market size and the fact that innovations flowed, and will continue to flow, from the well-funded petroleum exploration sector into uranium and gold exploration, and then to based metal exploration. As in other domains, technological innovations are usually neglected at the beginning until a market explosion. Portable XRF and infra-red instruments are good examples of innovative products that will progressively reach maturity.

A way to recognize disruptive innovation is to identify the disappearance or appearance of professional people. The role of prospectors has clearly undergone a progressive decline, but is still significant in grassroots exploration projects. Professional exploration geologists (G1), geophysicists and geochemists (G2), and remote sensing specialists and database managers (G3) reflect the arrival of new techniques in mineral exploration. Within the field of geology, frontier research involving new sets of concepts has the capacity to change approaches significantly, such as stratigraphy applied to stratiform deposits (Samama, 1986), volcanology adapted to epithermal systems (Sillitoe and Bonham, 1986), or more recently, volcanology applied to diamond-bearing kimberlites (Jakubec, 2008). It reflects the greater consideration for actualism in metallogeny.

Organization of mineral exploration has been continuously reshaped, first by the development of Taylor-style mining exploration teams within companies, then by the segmentation of knowledge and value chains between service and production through the institution of junior mining companies. Companies played a prominent role because each major company developed its own (often private) set of competencies. The continual leaking and exchange of knowledge, either voluntary or not, through human resource mobility, conferences, visits or publications led to a punctuated equilibrium model, with each company successively adopting the same organizational form. State roles in exploration changed during each of the three globalization waves and during the inter-globalization periods. They usually played an economic pro-cyclic role by helping to open up new territories, develop technologies (airborne surveys for instance), provide geo-information and train highly qualified people. The state also mitigates mining development with social aspects, such as conservation, the environment and social responsibility. For instance, the Canadian 43-101 and Australian JORC guidelines and definitions steer the industry’s approaches toward more rigorous mining and exploration methodologies, particularly regarding analytical aspects.

Innovations and globalizations

In theory, innovation booms should precede globalization: it is the accumulation of technological discoveries and their increasing use in society that allow favorable economic periods marked by greater worldwide exchange (Abernathy and Clark, 1985). Globalization increases inter-company competition and thus the need for competitive innovation. This promotes a positive feedback loop, creating welfare and an increased demand for mineral resources, and supporting more innovations.

However, the history of innovations in mineral exploration does not display a regular pattern. The first globalization began in the 1870s and the major innovations in either targets or technologies only occurred at the end of the century. The second globalization displayed a rather similar relationship, with the use of new geophysical and geochemical techniques toward the end of the period. The present (third) globalization appears more influenced by the rise of new technologies. Even if history clearly demonstrates that once the demand for a metal has been created, exploration delivers (Laznicka, 2010), the largest deposits were nonetheless found mainly at the end of each globalization period, or even during the inter-globalization periods. This is due to the very long time delay between metal demand, technological improvements and their application in the field, and the number of projects in the pipeline at the end of a globalization period.

The effect of globalization on mineral exploration is twofold: on one hand, it significantly increases the demand, requiring new mines to be developed; on the other hand, it diversifies the demand and places constraints on more exploration activities due to a growing environmental awareness: land conservation and human resources policies during G1, environmental management during G2, and the carbon footprint and social responsibility during G3.

Specificity of the mineral exploration innovation system

The innovation chain in mineral exploration has several unique features when compared to the better-described biotechnology or computer software industries (Beaudry et al., 2006). However, it also shares a number of similarities with other domains in that it is possible to distinguish technical innovations from social/organizational innovation processes (Van de Ven et al., 1999). Since the beginning of the mineral exploration industry, both technical and organizational innovations were shared with other segments of the industrial world. Several technical innovations came from the military industry, such as the airborne geophysical surveys or, more recently, on-the-spot geochemical analysis. Many innovations were used in both civil engineering and mineral exploration, from Nobel's dynamite to microseismic surveys to numerical codes for geomechanical simulations.

Organizational innovations have also been shared with other industries: the Taylor-style of organization reshapes exploration teams at the beginning of the 1900s, moving to more horizontal, matrix-style structures by the end of the century. Organizational innovations allow for better use of inventive resources and new technologies, which has been considered a necessary pre-condition for technological innovation (Lam, 2004). At the same time, the few disruptive technologies used in mineral exploration helped reshape the organization, such as the development of airborne geophysics or geopositioning. Schumpeter (1950) saw organizational changes and new products, processes and markets as factors of “creative destruction.” Organizational and technological innovations are intertwined (Lam, 2010).

Target innovations have not followed the habitual innovation chain from fundamental discovery to development, scaling adaptation and application. They flow almost directly from mining exploration companies to universities. Therefore, the knowledge flux is backward in the early days of establishing a new type of deposit, moving from industry to academia where it initiates research. The exchanges that ensue re-organize the flow of information into a more classical innovation transfer from fundamental to applied research.

Intellectual property has sometimes been kept secret for several years, such as some features of the porphyry copper model before the landmark publication of Lowell and Guilbert in 1970. Even today, some key elements of the New Caledonia lateritic nickel model or the Australian IOCG model have never been published. But because intellectual property usually experiences only short-lived protection, the innovation chain is typically short and fast. Target innovations have been increasingly shared between mining companies for most types of mineral deposits. The innovation chain became a cooperative competition (co-opetition) activity. Following this model, several aspects of research innovations, particularly for targets, were developed by university-industry-government consortia, allowing cost sharing and the organization of sensitive intellectual property. This type of structure is particularly well suited to an industry where there is strategic interdependence between firms, such as junior and major companies at the exploration stage, and between major companies at the development stage. However, these consortia have until now been limited to specialized sectors of the mining industry (gold, base metals), with limited exchange with other sectors, such as the petroleum industry.

CONCLUSIONS

The mineral exploration industry has been innovative since its origin. It has answered the demand for metals by renewing its targets, geological and economic concepts, technical methods, and even its organization in order to discover more mineral resources. The long-term evolution innovation chain in the mining exploration industry has been shaped by internal and external factors. External factors include demand and economic and political context. Internal factors are related to the development of the industry itself, such as the dynamics of its innovations.

External factors

External factors have played a dominant role. The demand for new metals creates new branches of the mineral industry and promotes the development of new fields of research, from nickel during the first globalization to rare earths at the present time. Intense exploration activities resulting in discoveries have always correlated with high metal prices.

The domain is evolving toward ever-more diversified activities, with a pronounced specialization among the different segments of the industry. Coal and petroleum geology used to be part of economic geology at the beginning of the twentieth century, but were distinguished as a specialized discipline after World War II. A new style of professionals appeared with progressive development in the fields of geophysics, geochemistry and geomatics following disruptive technological innovations. Ore deposits are being discovered deeper than ever before, requiring more innovations. Although geological reasoning has remained the core business of explorationists (Sillitoe and Thompson, 2006), high-tech advances in exploration practices have transformed the way discoveries are made by increasing the speed of discovery, the capacity of target selection in vast and underexplored territories, and the depth of detection.

The relative economic importance of the mining industry has been declining in Western societies since the first globalization period. Mining research and innovations were at the root of many respected universities and colleges all over the world, but mining departments were progressively replaced by other disciplinary domains that offer new expectations; academics have consequently been moving from national capital centers toward regional, even marginal universities since the 1970s. This creates a negative feedback loop, with less involvement from highly qualified people and less challenges.

Internal factors

Each domain is also influenced by its own dynamic that was likely influenced by key entrepreneurs (Schlumpeter, 1950) or by a sporadic, even chaotic, sociological evolution (Kuhn, 1962; Hung and Tu, 2011). The long-term history of mining evolution shows different degrees of change, periods of dislocation, and loops between continuity and discontinuity. Innovation rates increased over super-cycle periods, beginning with the development of previous technological disruptive innovations, followed by target innovations that take decades to be developed. From the initial discovery, other deposits of the same class are discovered, and a circle of understanding and discoveries develops — a positive feedback loop — sustaining an incremental innovation process. Most major technical innovations came from outside the geological sciences, except for geostatistics and geodynamics.

Mineral exploration has long been practiced all over the world. However, its solidification as a discipline only occurred in a limited number of countries. Internationalization, as exemplified by the migration of highly qualified miners from Saxe or Cornwall, has often been counterbalanced by a very national, sometimes secretive approach. European and American scientists diverged in the 1960s, when the style of the discovered deposits appeared very different — more magmatic in America, more sedimentary in Europe. The east-west international mobility of expertise was low during the Cold War, which allowed Russian scientists to develop their own approach, such as lithogeochemistry. Many publicly held French and Russian mining companies still use non-conventional approaches in their definition of mining reserves, developing very early geometallurgical approaches or innovative geophysical techniques. The fact that mines and smelters are mostly located in remote areas probably also acts as a deterrent for new professionals who aspire to further their careers by moving from company to company (Filippou and King, 2011). Linguistic isolation played a significant role, allowing original schools to develop with the risk of parochialism.

Another internal factor that played a significant role in the evolution of innovation in mining exploration is the generation effect (Attias-Donfut, 1988; Winock, 2011). Each generation is marked by a major event that constructs the mind of the communities and orients their challenges and actions during a large part of their working life. The mobility of Cornish miners at the end of the nineteenth century has been inscribed in the genome of numerous mining countries: a quarter of a million descendants of those miners currently live in Bendigo, Victoria, Australia. Several key discoveries, such as Bingham, El Salvador, Kidd Creek or Olympic Dam, have long remained in the mind of, and shaped the thinking of a whole generation of, key explorationists. More work is needed to understand the long-term influence of these historic events in shaping the mind of innovators and the development of the mining industry.

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Appendix: scientometric methodology

In order to complete this historical overview of innovation in mining exploration, a limited scientometric survey was carried out on the *Economic Geology* journal, the oldest and most respected publication in the domain. Every decade, a year was studied in order to determine the origin (institution, place) of the authors for each paper and the theme of the research. During the early years (1900–1920), the origin of the author was usually unclear and thus some uncertainties persist/exist.

TABLE

Table 1: Technical and target innovations since the first globalization event

FIGURES

Figure 1: A: National origins of authors since 1920 in Economic Geology; see methodology in appendix. Showing the decline in American authorship, the dominance of Canadian authors since 1990, and the sharp increase of articles from Australia and the rest of the world; B: Professional origins of authors since 1920 in *Economic Geology*; see methodology in appendix. This figure shows the dominance of papers from national geologic surveys in 1920 and 1950, the increase of papers from the industry from 1960 to 1970, and the dominance of academics since 1960. It also shows the rising number of authors per contribution since 1910, demonstrating a notable progressive increase in the number of contributors since 1960, representing a change in the structure of research that requires more collaboration.

Figure 2: Discovery year for principal world-class mineral deposits within the super-cycle framework, with some key discoveries. List of ore deposits (based on Rundqvist et al., 2006 and completed by the author).

Figure 3: The relative popularity of Pluto and Neptune over the years. From Mackay (1954) and completed using data from Davis (1988) and the author.

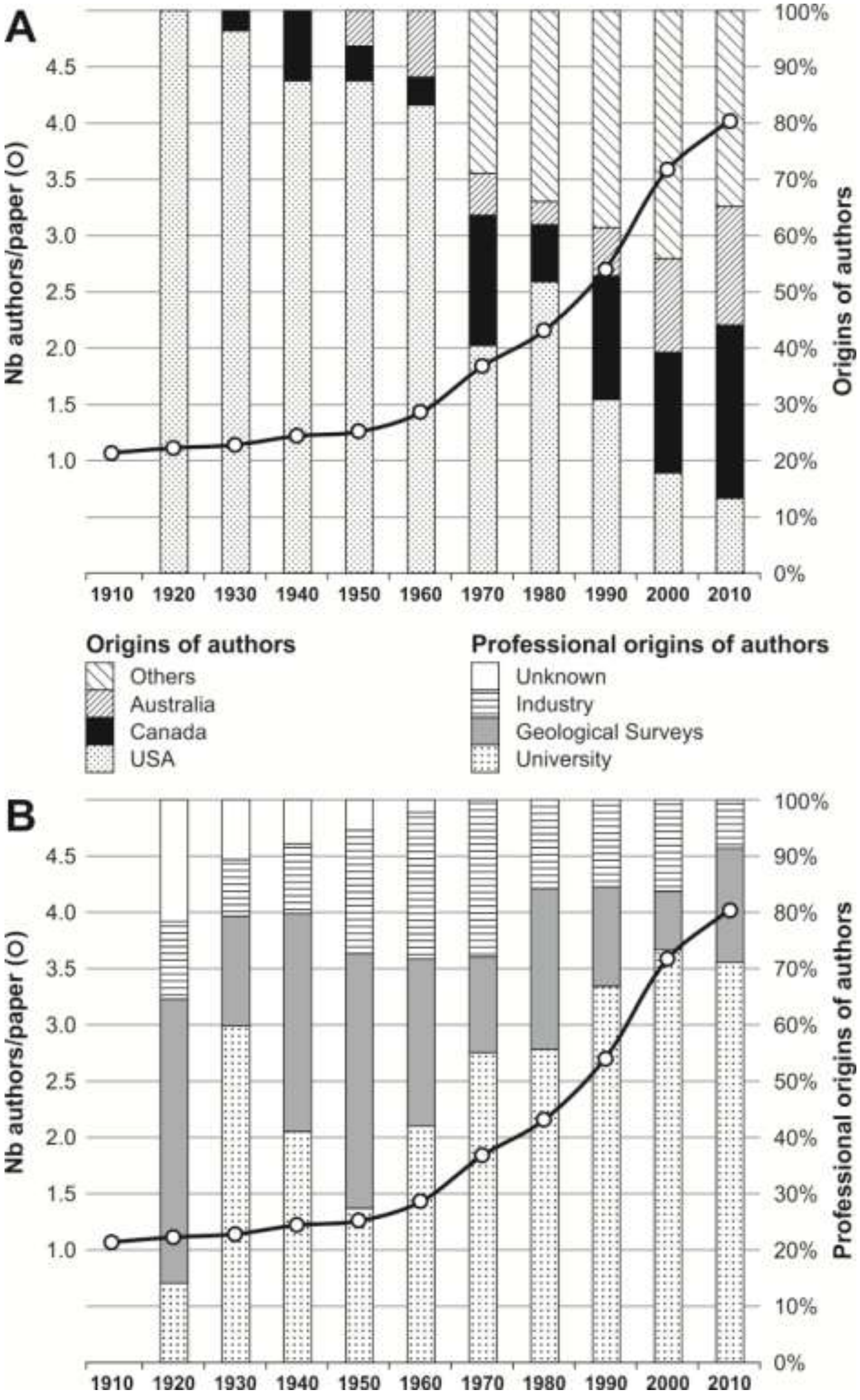
Figure 4: Evolution of the production chain in mineral exploration since the nineteenth century in Western countries, and evolution of the copper price (US constant $).

Figure 5: Incremental and disruptive innovation over the past ten years in the mineral industry of Eastern Canada: ICP-MS analysis (A), new web claim designation in Quebec (C), Air-born Gravimetry (G), Computer data-integration (I), GPS technology (P) and new ore deposits metallogenic models (M).

	Major discoveries	Major technologies	Organizations
Before G1 (1800–1870)	Native Cu (Michigan), Au placers and epithermal veins (Pacific rushes), massive Cu (Rio Tinto), diamonds (Kimberley, 1867), Minas Gerais Au (Brazil), Cr (Turkey)	Railways, security lamps, geological mapping, drilling, gold rush technologies, spectrometry, cyanidation	Organization of the first geological surveys (BGS, 1835); School of Mines (Columbia, 1864) Creation of early major companies (Billiton, 1860)
G1 (1870-1914)	Porphyry Cu (Bingham, Chuquicamata), bauxite Al (France), lateritic Ni (New Caledonia), Copperbelt (Congo), Tsumeb (Namibia), Rand Au (SA), BIF (Mesabi Iron Range, USA), Colorado Pb, Kiruna Fe (Sweden), Nikopol Mn (Russia), Kalgoorlie Au (Australia), Bushveld (SA), Broken Hill, Renison (Australia), Sudbury Ni (Canada)	Compressed air drilling, nitroglycerine, rotary drilling, spectroscopy, Cu-hydrometallurgy, Al-electrolysis, supergene enrichment	Establishment of geological surveys (USGS, 1879) Creation of major companies: Mitsubishi (1871), Rio Tinto (1873), Peñarroya (1881), BHP (1884), Alcoa (1888), ASARCO (1899), Teck (1913), UHMK (1906)
Between G1-G2 (1914–1945)	Abitibi Au, Cu-Zn (Canada), Colorado Au, Boliden Cu-Au (Sweden), phosphates Morocco, Mt Isa Cu (Australia), Norilsk Ni (USSR), Kola phosphates (USSR), Climax Mo (USA)	Petrology, development of geophysics	Pechenga (1921), Noranda (1922), Norilsk (1939) BRPM (1921) in Morocco
G2 (1945–1973)	Porphyries (Ertsberg, OK Tedi, Bougainville, PNG; Sierrita, Twin Buttes, USA; Island Copper, Canada), Palabora (SA), Carlin Au (USA), Niger U, anorthosite Ti (Lac Allard, Canada), tropical bauxites, Australia BIFs, Rossing U (Namibia), Elliott Lake U (Canada), Colorado U, Muruntau Au (USSR), Abitibi VMS (Canada), Carlin Au (USA), Kambalda Ni (Australia), Ireland Pb-Zn, Kupferschiefer (Poland)	SX-EW, airborne EM and Mag, sedimentology, radiometry, lithogeochemistry (USSR), mass spectrometry	Creation of national companies: Potash, Cameco (U) in Canada, Cogema (U) in France; CVRD in Brazil, Codelco in Chile Development of geologic surveys
Between G2-G3 (1973–1995)	Porphyries (La Escondida, Chile), lamproite diamonds (Argyle, Australia), first IOCG (Olympic Dam, Australia), massive Cu (Neves-Corvo, Portugal), deep VMS (La	Emergence of remote sensing, (Landsat 1, 1972), geochemistry (litho- and secondary environment), structural geology, INAA and ICP	Reduction of geologic surveys, closing of US Bureau of mines Development of junior companies (1985)

	Ronde, Canada), Bjokdal Au (Sweden), Cantung W (Canada), Red Dog Zn-Pb (Alaska)	analysis	
G3 (since 1995)	IOCG (Chile, Australia), epithermal Au (Yanacocha, Peru), Canadian diamonds, porphyries (Oyu Tolgoi, Mongolia; Reko Diq, Pakistan), Mo-Re shale (Merlin, Australia), HPAL lateritic Ni (Australia, Cuba, New Caledonia), Copperbelt (Zambia, Congo), Mirabela Ni (Brazil)... and more to come	Development of remote sensing (multispectral), airborne gravimetry, deep EM, data integration (GIS), in-situ analysis, GPS, ICP-MS	Fusion of major companies, emergence of BRIC mining groups, transformation of geologic surveys

Chemical elements: Al= aluminum, Au= gold, Cr= chromium, Cu= copper, Fe=iron, Mn=manganese, Mo= molybdenum, Ni=nickel, Pb= lead, Pt= platinum, Re=rhenium, Ti= titanium, U=uranium, W= tungsten, Zn=zinc. Other abbreviations: BIF=banded iron formation, BRIC= Brazil-Russia-India-China, EM= electromagnetic, GIS= geographic information system, GPS= global positioning system, IOCG= iron-oxide copper gold, ICP-MS= inductively coupled plasma mass spectrometry, INAA= instrumental neutron activation analysis, PNG= Papua New Guinea, SA= South Africa, SX-EW= solvent extraction-electrowinning of cathode copper, VMS=volcanogenic massive sulfides.



A
B
Nb authors/paper (O)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
Origins of authors
Professional origins of authors
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Origins of authors
Others
Australia
Canada
USA
Professional origins of authors
Unknown
Industry
Geological Surveys
University

Figure 1

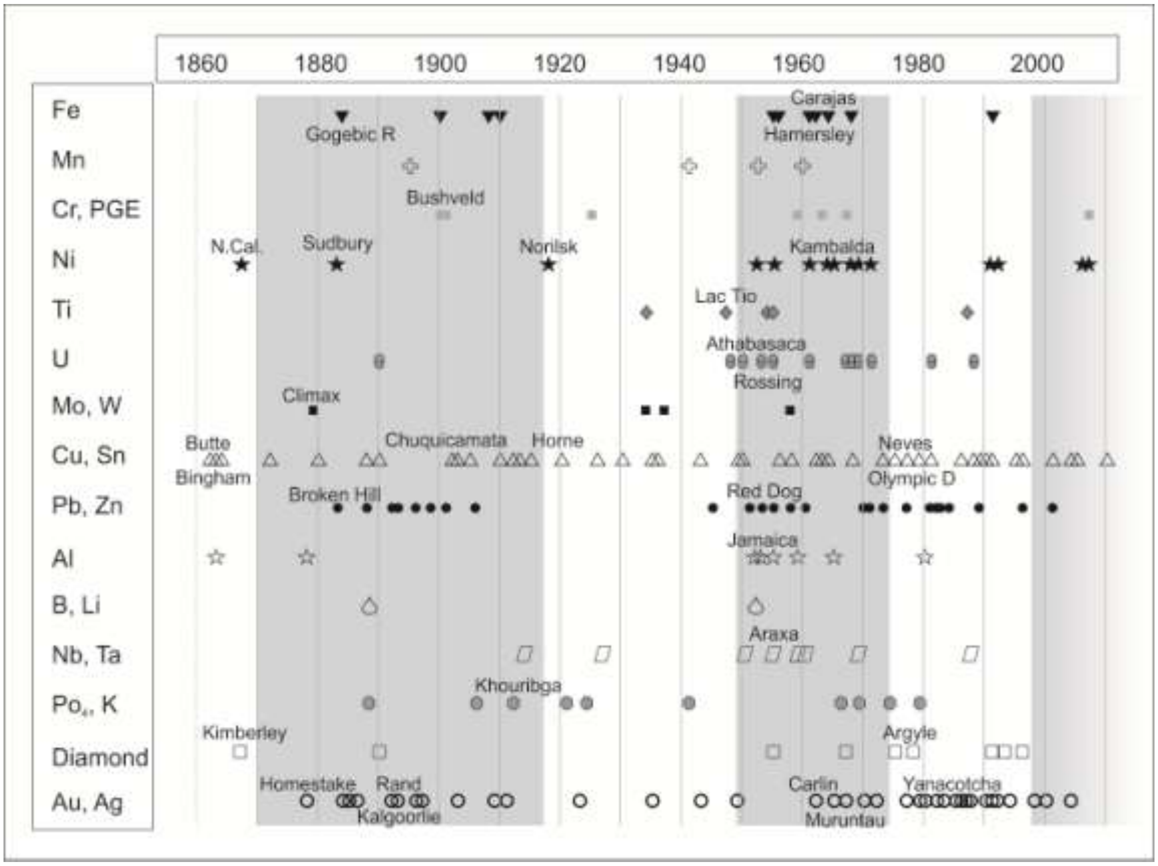

1860
1880
1900
1920
1940
1960
1980
2000
Fe
Mn
Cr, PGE
Ni
Ti
U
Mo, W
Cu, Sn
Pb, Zn
Al
B, Li
Nb, Ta
Po4, K
Diamond
Au, Ag
Carajas
Gogebic R
Hamersley
Bushveld
N.Cal.
Sudbury
Norilsk
Kambalda
Lac Tio
Athabasaca
Rossing
Climax
Butte
Bingham
Chuquicamata
Horne
Neves
Olympic D
Broken Hill
Red Dog
Jamaica
Araxa
Khouribga
Kimberley
Argyle
Homestake
Rand
Kalgoorlie
Carlin
Muruntau
Yanacotcha

Figure 2

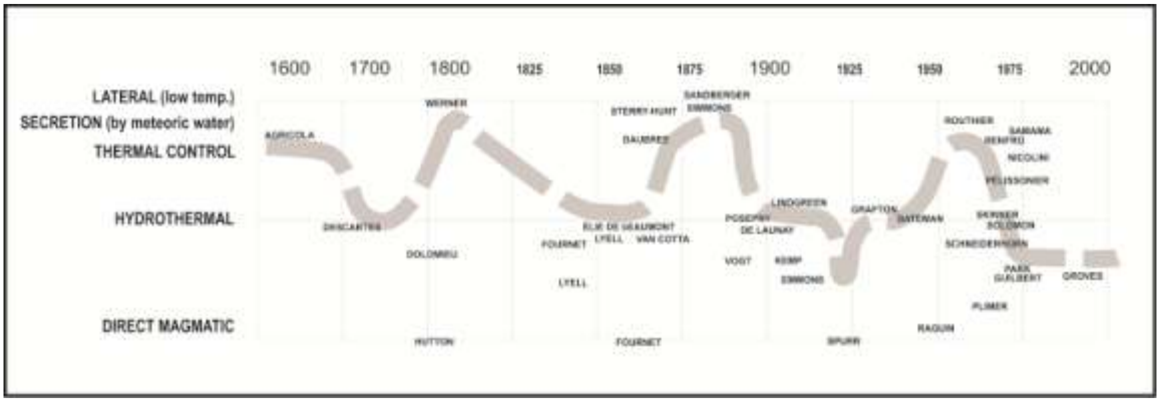

1600
1700
1800
1825
1850
1875
1900
1925
1950
1975
2000
LATERAL (low temp.)
SECRETION (by meteoric water)
THERMAL CONTROL
HYDROTHERMAL
DIRECT MAGMATIC
AGRICOLA
WERNER
DESCARTES
DOLOMIEU
HUTTON
FOURNET
LYELL
STERRY HUNT
DAUBREE
SANDBERGER
EMMONS
ELIE DE BEAUMONT
LYELL
VAN COTTA
FOURNET
POSEPNY
DE LAUNAY
LINDGREN
VOGT
KEMP
EMMONS
SPURR
GRAPTON
BATEMAN
RAGUIN
ROUTHIER
SAMAMA
RENFRO
NICOLINI
PELISSONIER
SKINNER
SOLOMON
SCHNEIDERHOHN
PARK
GUILBERT
GROVES
PLIMER

Figure 3

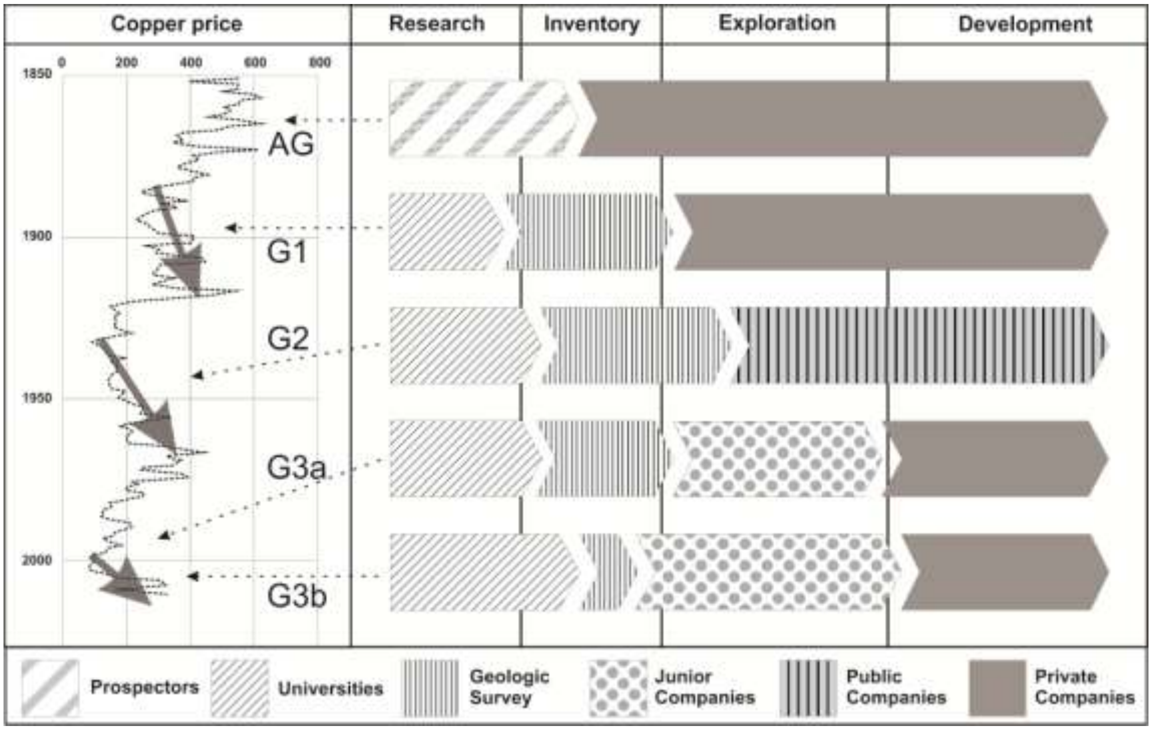
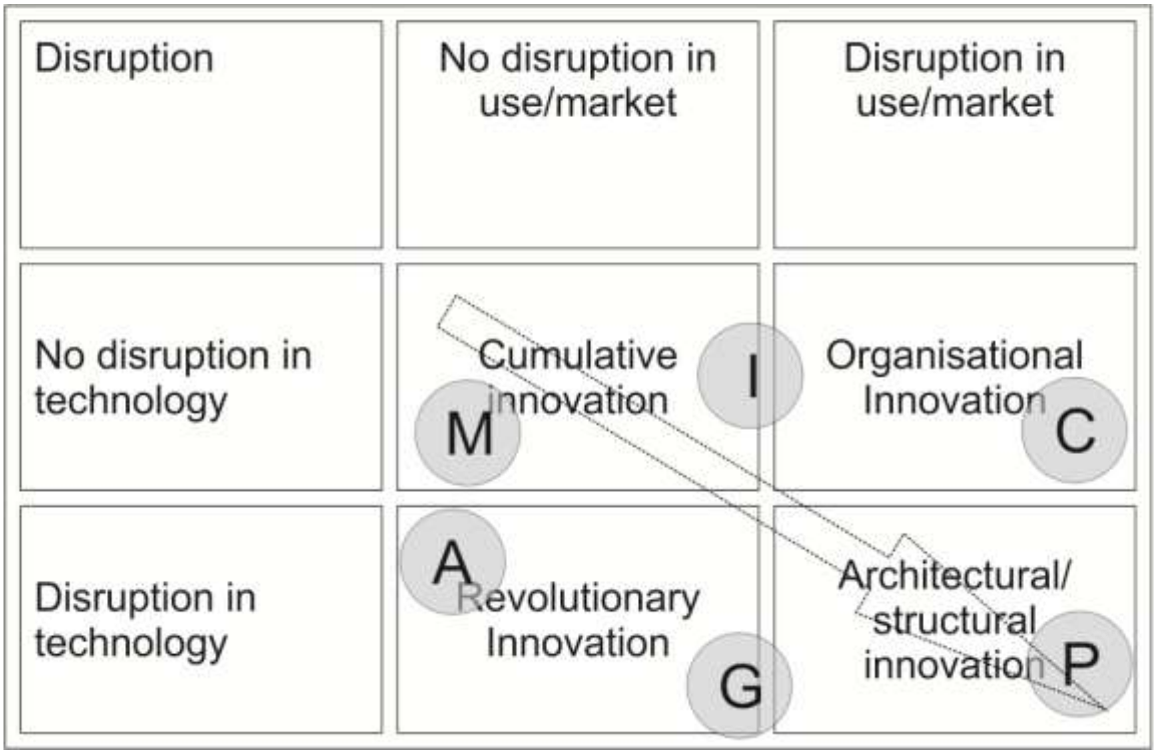

Copper price
Research
Inventory
Exploration
Development
0
200
400
600
800
1850
1900
1950
2000
AG
G1
G2
G3a
G3b
Prospectors
Universities
Geologic Survey
Junior Companies
Public Companies
Private Companies

Figure 4



Disruption	No disruption in use/market	Disruption in use/market
No disruption in technology	Cumulative innovation	Organisational Innovation
Disruption in technology	Revolutionary Innovation	Architectural/ structural innovation

Figure 5