A Historical Review of Mining Automation in Mexico

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Abstract

The increase of mining in certain historical periods can be attributed to the incidence of various factors, such as the price of metals, technological development, and economic and environmental policies. This paper reviews the most important periods of mining development in Mexico, examining in depth the most recent period: the implementation of automation. The majority of social analyses related to mining have focused on the concept of neo-extractivism and have emphasized economic policies and prices. This paper's contribution is a review of the data of the revolution in the mining sector's productive forces. This is an aspect that may be as important as metal prices and the sector's economic policies when seeking to understand the current situation.

Keywords: mining; automation; gold and silver exploitation; technological development; translational companies; foreign investment.

1. INTRODUCTION

During recent decades, the increase in primary resource exploitation in Latin America has been described as "neo-extractivism" (García Zamora and Grinspun, 2015; Gudynas, 2009; Veltmeyer and Petras, 2015). Mineral exploitation is a case in point. This paper examines the transformations that have taken place in Mexico's mining economy and reflects on the role technology has played in gold and silver exploitation, particularly over the last three decades. Research suggests that both technological changes during the aforementioned period and as international prices increase are as important as neo-liberal economic policy when seeking to understand neo-extractivism.

Data pertaining to technological changes over the past three decades was obtained from the following sources: 1) bibliographic information, 2) more than ten interviews with technology providers and mining sector entrepreneurs, and 3) the Zacatecas International Mining Conference (Rim, 2018).[1]

To facilitate the analysis of mining production in Mexico, it is helpful to define four distinct historical periods.[2] The expansive pre-colonial period, during which minerals where predominantly used in the production of luxury goods, can be seen as being the first period during which gold and silver were systematically exploited with the express intention of using them to produce currency.[3] During the colonial period, metallic mineral production processes were based on the exploitation of indigenous labor. It has been established that labor was organized using the following systems, which are ordered chronologically: serfdom, slavery, bonded labor, and day labor (Bakewell, 1990).

The second period saw the development and implementation of new technologies in extraction, processing, and smelting processes, as well as the expansion of metallurgy to other minerals. This period began during the Porfirio Diaz dictatorship (the Porfiriato) and continued until the first three or four decades of the 20th century. During this period, the monoproductive practices of the colonial period, which were primarily concerned with the exploitation of silver, were abandoned, and production was diversified to include industrial and nonferrous metal production, such as lead, copper, zinc, iron and coal (Sariego *et al*, 1988).

The third period began during the period after World War II with the expansion of non-metallic mineral exploitation. Non-metallic minerals exploited during this period include sulfur, fluorite, and barite (Sariego *et al*., 1988). This period is understood as the period of import substitution industrialization (ISI), and also saw the consolidation of unionism in the mining sector. State intervention in the sector is also a key characteristic of this period, with the state's Mexicanization of mining program playing an instrumental role in this intervention.

According to the most common periodizations, which emphasize changes in government policy as a crucial variable, the fourth period of Mexican mining began in 1982, with the opening up of the economy to neoliberal policies, something which can also be conceived as a reaction against the interventionist welfare state (Anderson, 2003; Lopez and Eslava, 2013). This period was characterized by the reform of constitutional article 27, the signing of the North American Free Trade Agreement, and the implementation of new laws regarding farming, mining, and foreign investment. All this culminated in the Mexicanization program, which allowed large corporations to establish a presence in Mexico.[4] Productive processes also began to be automized during this period, a process which gained momentum during the 1990s and has continued to do so up to the present day.

This paper is made up of four sections. The introduction offers a brief summary of the four distinct periods in the history of Mexican mining. Section two describes the development of technology during the first three periods from a historical perspective, beginning in the colonial era then on to the Porfiriato, then finally on to the era of ISI. Section three offers an explanation of how the technological revolution which began in the 1990s led to radical changes in all phases of the metal extraction process, changes which have had significant implications for the economy. In the conclusion, the idea that mega-mining represents a significant shift in terms of production between the 20th and 21st centuries is presented.

2. THE FIRST STAGES OF TECHNOLIGCAL DEVELOPMENTS IN MEXICAN MINING

In this section, the first three periods of technological developments in Mexican mining will be analyzed. During the colonial age, the productive system was based almost exclusively on extraction and the trade in precious metals, in particular in silver. Mineral lodes where exploited using open excavation, with later excavations becoming deeper and eventually resulting in a network of narrow, twisting tunnels, which caused significant operational problems. This was known as the *sistema de rata* (rat system) in New Spain. The first technological advance made consisted of constructing galleries and sloping tunnels which connected the lower galleries, and improved ventilation, drainage, and mineral extraction. The first gallery intended to service mines was constructed in 1556, in Potosi mountain (Bakewell, 1990).

On the other hand, the first recorded use of explosives in mining extraction took place in 1627. Black powder was used in this first explosion and continued to be used until 1865 (Konya and Walter, 1991). Large ditches and galleries were perforated by underground explosions using black powder. Deeper ditches necessitated the use of a system of simple animal-driven winches to bring minerals to the surface (Brading, 1975). Processing techniques also evolved during

Spanish rule. Smelting was the first technological advance to be utilized, which allowed small quantities of minerals with high silver concentrations to be refined (Ramos Ramírez, 2014).

Other metal processing techniques that involved mercury and quicksilver rapidly became widespread. Around the year 1600, there were 370 *haciendas* which employed these materials in silver extraction (Bakewell, 1990). Techniques involving mercury or quicksilver allowed a wider range of minerals to be exploited, as well as enabling the use of hydraulic propulsion or animal-driven mills in grinding processes, depending on the availability of water in the surrounding area. Water was also used for cleaning purposes during the amalgamation process (Bakewell, 1976).

In hindsight, it seems that mineral exploitation was restricted by the underdeveloped productive forces which existed during the colonial period, especially when compared with output obtained using contemporary methods. For example, 56,144 kilograms of silver was exported to Europe during the period from 1521 to 1830, a period of over three centuries. When these figures are compared with the period from 2000 to 2010, during which 36,465 kilograms were produced, we can see that more than half the quantity of silver extracted during the entire colonial period was extracted during the decade 2000 to 2010 (González Rodríquez, 2011). Figure 1 shows the evolution of gold and silver production during the colonial period. It is clear that technology contributed to increased production levels.

Figure 1. Gold and Silver Production During the Colonial Period 1521-1821

Nomenclature:
1) construction of mineshafts (1556),
2) smelting techniques (1600s),
3) benefits of mercury and quicksilver (1600s), and
4) black powder (1700s).
Source: compiled by the author based on data from INEGI (2010), Bakewell (1976, 1990) and Brading (1975).

The second period is characterized by The Reformation and the stripping of the clergy's assists, resulting in the formation of a new, secular aristocracy which rarely engaged in economic activity. The so-called *hacienda porfiriana* was not a significant advance on the colonial model, as this new model did not do much to develop new processes, and only rich veins that were close to the surface were exploited. It did, however, capitalize on the benefits of international capital investment, particularly from the U.S.A (Rosenzwig, 1988).

The opening up of mining to foreign investment facilitated the consolidation of a new technological age, one in which mining productivity increased. One particularly salient aspect was the expansion of the rail network, given that 3,749 km (16%) of the 22,822 km of railway lines that existed in 1908 were exclusively for mining purposes (Sariego *et al*., 1988). This situation contributed to reduced transport costs for minerals (Bernstien, 1964).

Another important technological advance that under-pinned the mining boom during the dictatorship of Porfirio Diaz was the introduction of electricity. The first use of electricity in mining dates back to 1889, with the first large-scale electrical projects being built from 1900 onwards (Bernstein, 1964). In a mining context, electricity can be used for lighting, pumping, transporting loads of materials, as well as to power compressors used for ventilation and perforation (Sariego *et al*., 1988).

Another technological application which predates the invention of dynamite by Alfred Nobel in 1865 was the development of materials that were more energetically dense than black powder, such as gelatin dynamite, which was widely used between 1867 and 1950 (Konya and Walter, 1991).

The construction of various foundries was an important characteristic of the mineral processing period. The first plants in Mexico were built in Monterrey and Aguascalientes, in 1891 and 1894, respectively. The *Velardeña* plants, in Durango and Avalos, Chihuahua, were the next to be built, and processed 40% of the lead and 20% of the silver produced in the country (Sariego *et al.,* 1988). The introduction of this technique caused national gold production to rise from 1,477 kilograms in 1891 to 41,420 kilograms in 1910 (Bernstein, 1964). Around 1920, the process of selective flotation started to be used to treat oxides and sulfurs of copper, lead, and zinc contained in rocks. This technique allowed metallic compounds to be separated by using reagents, which can also be used in leaching, grinding, crushing, filtering, and drying processes. (Sariego *et al*., 1988).

Figure 2 displays the evolution of oil and silver mining production during the Porfirio Diaz dictatorship and the ISI period. It can be observed that silver production began to accelerate after 1891. This growth is due to the combination of foundries being constructed and the adaptation of cyanidation as the principal extraction method. The year 1905 was an exception to this trend, due to the effects of the monetary reform which took place this year and led to Mexico abandoning the silver standard (Sariego *et al*., 1988).[5]

Figure 2. Gold and Silver Production During the Porfirio Diaz Dictatorship (second period) and the ISI era (third period).

Nomenclature:
1) Gelatin dynamite (1867),
2) electrification (1889),
3) foundries (1891),
4) Cyanidation (1891)
5) Simple mechanization (first decades of the 1900s)
6) flotation (1920)
7) intensive mechanization-diesel and electro mechanics machinery (1950s)
8) ammonium nitrate (ANFO) (mid-1950s),
9) rock mechanics (1970s),
10) automatization 1980s).
Source: compiled by the author based on data from INEGI (2010), Sariego et al. (1988); Bernstein (1964); Konya and Walter (1991), and Ramírez and Alejano (2004).

The Mexican Revolution only impacted on mining production during the first few years of the conflict. Silver production fell from 2,305,748 kilograms in 1910 to 1,230,750 in 1915 (INEGI, 2010). However, the price increase caused by World War I (1914-1918) caused the situation to recuperate after 1916 (Tello, 2008). During World War II, the U.S.A. was the principal destination for Mexican exports. This is true of manufacturing and agricultural products as well as minerals. In fact, agricultural and manufacturing exports exceeded mining exports, and silver production fell from 2,520,394 kilograms in 1940 to 1,900,352 kilograms in 1945, while gold production fell from 27,468 kilograms to 15,530 kilograms during the same period (INEGI, 2010; Tello, 2008).

The third period of mining production began in the post-World War II period and saw mining production increase during the period 1958 to 1970. However, mining never constituted more than 20% of total exports. In 1959, mining represented just 5% of GBP, despite the fact that Mexico was the world's largest producer of silver, the second largest producer of sulfur, fluorite, and bismuth, the third largest producer of lead, and the fourth largest producer of zinc and barite (Tello, 2008). The implementation of the 1961 Regulatory Act of Constitutional 27 concerning Exploration and Utilization of Natural Resources was an attempt to ensure the State and national capital controlled the mining sector, as well as to foster growth in the sector while directing production in such a way to prioritize the national industry and market (Delgado Wise and Del Pozo Mendoza, 2001).

This new law decreed that Mexican capital had to have a majority share in all mining companies, meaning that mining concessions were only granted to companies that were at least 51% Mexican owned. Tax breaks caused the process of Mexicanization to accelerate to the extent that, by 1971, Mexican capital had a majority share in nearly all mining companies, although foreign capital was never totally pushed out (Urias, 1980). Mexicanization, however, did not bring about in significant productivity gains, with the exceptions of coal, copper, and iron. Production levels of metals, such as silver, lead, and zinc stagnated (Delgado Wise and Del Pozo Mendoza, 2001).

The introduction of electro-mechanical and diesel machinery in the 1950s made it possible to exploit porphyry stockpiles and engage in open-pit mining. Large-capacity machinery facilitated these processes, making the exploitation and processing of minerals with low metal concentrations profitable. The processes of intensive mechanization and the deprofessionalization of mining work also began during this period, part of an over-arching process of progressive substitution of manual work and simple mechanization, put in motion during the first decades of the 20th century (Sariego, 1988).

Machinery such as drills, explosive loaders, reamers, flyers, haulage equipment, transports, ventilation and drainage equipment, grinders, mills, and flotation cells, to name just a few, played a crucial role in extractive and processing operations. Practically every stage of the productive cycle became mechanized to some degree.

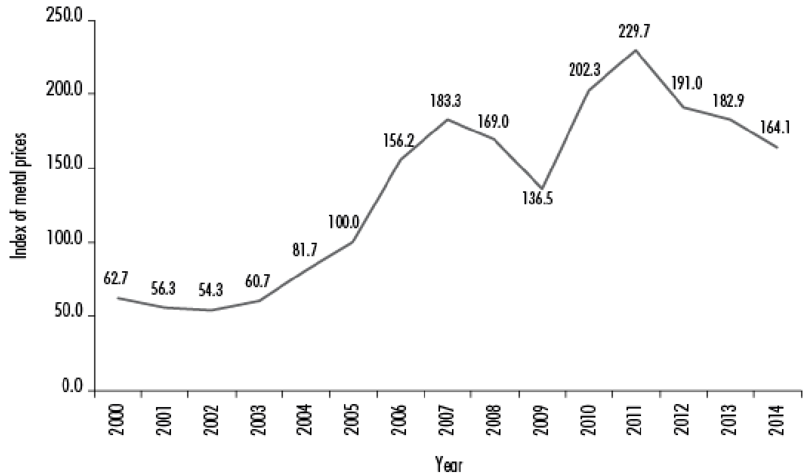
The development of rock mechanics allowed the behavior of rocks to be understood, in turn allowing for improved planning of mining operations. Although rock mechanics was first studied towards the end of World War II, its development intensified during the 1960s (Ramirez and Alejano, 2004). During the mid-1950s, a new explosive named ANFO appeared, which consisted of ammonium nitrate and diesel. ANFO was much more cost-effective than dynamite and flooded the mineral extraction market (Konya and Walter, 1991). Subsequently, during the 1960s and 1970s, new products called hydrogels and emulsions were produced. These new products replaced dynamite in all industrial sectors (Konya and Walter, 1991).

3. FOURTH PERIOD: AUTOMATIZATION

The fourth period began at the beginning of the 21st century with the international rise in metal prices which took place during the peak of the expansion of neoliberal economic policy (see Figure 3). In Mexico, this price increase led to an increase in the production of a wide range of metals, such as gold and silver (see

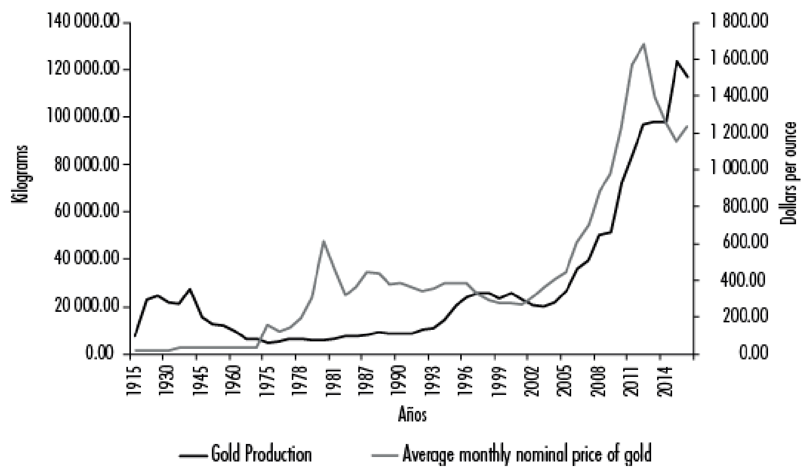
Figures 4 and 5).

Figure 3. Index of Metal Prices 2000-2014 (2005 = 100)



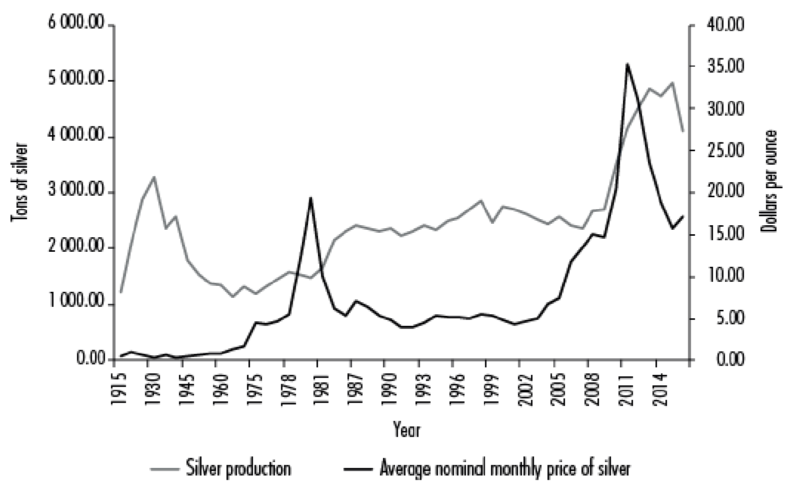
Source: International Monetary Fund, as cited by SGM (2015).

Figure 4: Gold Production in Kilograms, 1915-2016 Versus Average Monthly Nominal Price per Ounce in Dollars



Source: compiled by the authors based on data obtained by INEGI (2010)
(years 1915-2008), CAMIMEX (2017a) (years 2009- 2016) and Macro Trends (2018).

Figure 5. Silver Production in Tons 1915-2016 Versus Average Monthly Nominal Price per Ounce in Dollars



Source: compiled by the author based on data from INEGI (2010) (years 1915 -2008) Camimex (2017a) (years 2009-2016, and Macro Trends (2018).

Government policy designed to encourage foreign investment in mining made it easier to administrate expansive territories in Latin America. However, a review of the technological changes relating to open-pit mining that took place from the 19990s onwards reveals that a significant technological change took place at practically every stage of the productive process, resulting in a substantial productivity increase in the mining industry. This increase in productivity had the potential to open up some of the most remote locations in the world to mining, independent of neoliberal policies designed to facilitate mining companies' access to resources. In most cases however, political support was essential. The third industrial revolution, which is still ongoing, has seen advances in the design of automated processes. These successes led to a technological revolution in mining which began in the 1990s. Although this sector may not be one of the leading sectors in terms of implementation of automatic processes, changes caused by automatic processes have affected the sector over the last two decades.

For automatization to be effective for all productive processes, three crucial components must be integrated: 1) identification of information related to the functioning of machinery and equipment, 2) the processing of this information, and 3) monitoring. In the absence of automated systems, mining operations have to be closely monitored in order to guarantee their effective development. Carrying out this monitoring can present a number of risks to personnel, given the close proximity to powerful machinery, exposure to hydraulic and electrical power, falling rocks, and exposure to powders and gases caused by explosives. Mining companies recognize that these risks, as well as posing a threat to their workers' safety, lower their production index. Although automated systems were first developed during the 1970s, they are still being optimized (Ralston *et al.,* 2014).

Fully automated mines incorporate three technological tiers that are in constant interaction with one another: the first consists of mining equipment which contains electronic components, such as intelligent sensors. This equipment includes drills, reamers, loaders, and transport machinery. The second consists of communications systems, while the third consists of an intelligent platform which is capable of planning and monitoring operations (Li and Zhan, 2018).

Understanding how microelectronic, optoelectronic, and satellite technologies have been applied to the vast majority of devices, instruments, machinery, as well as to management and monitoring processes, is crucial to understanding the industrial revolution currently taking place in the mining sector. The MEMS (Microelectromechanical Systems) on which microelectronic technology is based enable devices to be miniaturized using micrometers, and in some cases are even capable of achieving nanometric proportions and mechanical movement properties which are widely employed in sensors, actuators, and energy converters. Much of this technology has been developed accumulatively over one or two decades. This development was made possible after a qualitative leap occurred at the end of the 1980s, which enabled equipment to be reduced in size, a higher degree of connectivity between equipment, the acceleration of the analysis process, an increase in the range of object exploration (satellite), and the possibility of using real-time information throughout every stage of the monitoring and decision-making process.

This qualitive leap was the result of diverse factors, such as the falling costs of various electronic components, such as sensors, as well as the development of data analysis platforms equipped with visualization interfaces. The increase in the number of sensors installed in equipment led to an increase in the volume, variety, speed, and value of data generation. This in turn resulted in the need for mining companies to develop ways to internally store, process and analyze large quantities of data in real time, although contracting a specialized company to provide these services is also an option (Hashem *et al*., 2015).

The technological revolution in mining has also brought about a significant reduction in the size of equipment. In geophysics, for example, the old portable mineral analyzer XRF (X-Ray Fluorescence) weighed over 30 kilograms in the late 1980s (Cufari, 2016). The manual Niton XR-F was produced in the 1990s, which had increased analysis capabilities and weighed only 1.5 kilograms (Thermo Scientific, S/f).[6] Using sophisticated sensors, it is now possible to carry out gravimetric calculations to detect tiny variations in the earth's gravitational field and identify areas with heavier mineral. Additionally, the use of laser optical methods in aerial devices allows for the precise altimetric measurement of the earth's surface to between 5 to 20 centimeters of accuracy (Jébrak and Vaillancourt, 2012).

The most widely-known aspect of the 1990s' technological mining revolution is open-pit mining. Although this technique predates the technological revolution of the 1990s, and had been conducted on a large scale since the mid-20th century for certain minerals in countries in which suitable conditions existed, a drastic change in the way it was conducted occurred during the 1990s. Namely, automatization allowed for systemic increases in the size and visibility of open-pit mining, as well as in the extent of interconnectivity between all stages and productive processes in mining. This is in contrast to earlier forms of exploitation which, regardless of size, used isolated production islands for different stages of the productive process.

Space is one of the main natural obstacles that capital faces when investing in mining. There are several crucial spatial considerations that make space a key variable, such as geographical location, distance from population centers, ports, and communication routes, climate, topography, geographical characteristics of the soil, and the cut-off grade (lowest quantity of mineral a material needs to contain in order for it to be a profitable mining material, rather than waste or barren material.) Another crucial spatial consideration is the environment from which the material is extracted. There are crucial spatial differences between deep-mining and open-pit mining. Deep mines, for example, are forced to use relatively small equipment and use machines under conditions with limited space, thin air, the possibility of toxic gases, and with the necessity of regular maintenance of the galleries' rooves and walls, in addition to other spatial restrictions

The aforementioned restrictions do not apply in open-pit mining operations, in which the quantity and size of machinery does not need to be significantly restricted. In such situations, space is neither an obstacle to the mobilization of fixed capital and input costs, nor to the transport of extracted raw materials and waste. In comparative terms, for example, once deep-mine excavations have been carried out, the quantity of sterile material extracted tends to be insignificant in comparison to the enormous quantity that can be systematically extracted from open-pit mines. Spatial restrictions which exist in deep mines do not apply to open-pit mines, resulting in significantly reduced costs.

These technical differences have economic implications, as open-pit mining allows for more highly-intensive work and more rapid returns on investment than are possible in deep mining. This difference has been a decisive factor for the decision to transition from deep mining to open-pit mining in areas where it is possible to do so. However, given that high-grade zones have already been exploited and consequently, in the majority of cases the quantity of sterile material is higher than the quantity of mineral, the profitability of open-pit mining was dependent on the development of sensor and automatization technology.

The transition from deep-mining to open-pit mining requires increased levels of capital investment. Open-pit mines require higher levels of capital investment in order for them to be profitable. Additionally, contemporary exploitations must be carried out by top-tier translational corporations in areas where the cut-off grade is sufficient to guarantee returns on any capital invested and ensure sufficient profits can be made before the mine becomes depleted. A thorough preliminary evaluation of both the productive potential (exploration) and the costs and benefits must therefore be carried out, employing sophisticated equipment and techniques, and using a large quantity of variables in each case (Herrera Herbert and Pla Ortiz de Urbina, 2006).

The antecedents of large-scale open-pit mining can be traced back to the mid-20th century. In the U.S.A., the technique was first utilized in Ohio for coal exploitation, and later spread to other states. The key to these projects was heavy machinery that could adapt to ground which was relatively soft when compared to the harder ground in which other types of minerals could be found. Enormous machines, such as "The Tiger", "The Mountaineer", "The GEM of Egypt", and "The

Silver Spade", were employed in coal mines during the 1950s and 1960s. Each was capable of removing enough earth to fill between two and three buses in one shovelful. "The Mountaineer" was capable of loading 100 tons of earth per shovelful, while the 1967 "GEM of Egypt", which weighed 700 tons, could extract 200 tons of earth in one shovelful (Doyle, 2014). But this technology operated in isolation, without the connection to other stages of the productive process which occurs in modern mega-mining. Various authors agree that open-pit mining offers a number of advantages over deep mining:

> Increased volume of exploitable minerals, more flexibility in planning as the excavation progresses, lower levels of risk at work, the absence of size restrictions on machinery meaning there are no limitations on the degree to which work can be mechanized, less strenuous physical requirements on workers, increased productivity, higher tonnage per blast, the near inexistence of ventilation problems, and reduced cost per ton moved (Herrera Herbert and Pla Ortiz de Urbina, 2006).

On the other hand, Herrera Herbert and Pla Ortiz de Urbina also point out the following disadvantages: "equipment requires substantial investment which necessitates higher levels of finance, equipment is more sophisticated and therefore must be operated by a more highly-skilled workforce, natural atmospheric elements such as rain, snow, and mist, can have a significant impact, the different areas of work need to be more highly organized, and the existence of significant environmental impacts which need to be counteracted via sometimes costly recovery projects" (Herrera Herbert and Pla Ortiz de Urbina, 2006). The existence of both significant advantages and disadvantages mean that open-pit mining can only be carried out with enormous investments.

The technological revolution of the 1990s brought about radical changes in all stages of the metal extraction process. [7] In exploration, for example, advances in spectrometry made it possible to analyze dozens of elements simultaneously and, for certain metals, measure in milligrams the quantity of mineral per ton (Jèbrak and Vaillancourt, 2012). The X-ray fluorescence analyzer became manual and more powerful, which meant it was no longer necessary to take samples to a laboratory for analysis.

It has been possible to analyze soil and atmosphere composition using satellite technology (Aviris optical sensor) since 1997. This satellite is capable of remote sensing, which allows earth and atmospheric composition to be identified and measured by analyzing a wide range of electromagnetic radiation. Additionally, satellite technology allows for rocks to be mapped, which in turn facilitates exploration in areas which are difficult to access. The most modern mass balance methods employ sophisticated analytical techniques to calculate the quantity of chemical elements that were added to or displaced from a rock during its formation, which enables the distance between the analysis site and the site where mineralization occurred to be measured (CONSOREM, s/f).

Geographical information systems (GIS) made physical plans obsolete. GISs became more widely used towards the end of the 1980s, along with personal computers and satellites designed to capture geographical information, such as Landsat, as well as location-tracking software such as GPS (Smith, 1995.) The *Servicio Geológico Mexicano* (SGM) began its geochemical-mining mapping program in 1995.

> 1:50,000 scale geological-mining cartography advanced to cover 34% of national territory by December, 2012, or 667,037 km2, consisting mainly of geological terrain with a high potential to be exploited for mining purposes. This means 49% of the land that possibly holds mineral deposits has been mapped (DOF, 2014, p17).

Other software exists, such as Tensor, the first version of which was released in 1993, which measures the stress placed on rocks and elaborates maps based on this data, which are then used to identify potential gold deposits, among other uses (e.g., Delvaux, s/f). Geochemical methods also allow deeper deposits to be detected using surface analysis (Jébrak and Vaillancourt, 2012).

A wide range of trucks, as well as other methods of cargo and heavy load transport such as tractors, backhoes, draglines, and cargo trucks, have been equipped with interconnected data systems, systems which were created to reduce fuel costs and improve performance (Daniels, 2017). The modular system (Modular, s/f) has been widely-adopted, allowing trucks to be converted into convoys, rapid in situ repairs to be carried out, including engines to be changed in very little time, as well as the reparation of conveyor belts, reparations which, due to the weight and position of conveyer belts, used to force the whole production process to be halted. [8] Cellular phones are equipped with electric batteries and alternative motors in order to prevent malfunctions which require equipment to be taken away for maintenance from occurring. These module systems allow all aspects of a mine's operations to be connected to a single database and allow for the functioning of all equipment to be monitored in real time. Other occupational safety and emissions monitoring equipment are also being equipped with new technology (Jébrak and Vaillancourt, 2012).

Surface mining machinery constitutes a watershed moment in mineral extraction. This is powerful machinery that passes over layers of rock, then cuts through it, crushes it, and sends it to a convoy to be processed. It is capable of achieving high levels of precision by adjusting to the characteristics of the rock and the ore vein. One of the first machines of this type was the 3000 sm Wirtgen surface miner, first sold in 1983 (Wirtgen GmpH, s/f). By the early 21th century, this technology had been improved and today there are several brands on the market. These machines simultaneously carry out three processes which, previously, had to be performed separately, namely cutting, crushing, and loading. Depending on the machine, they can cut up to three meters across and over than 50 centimeters deep. The 600 horse-power Vermmer T1255TL Terran Leveler Commander III can cut up to 3.66 meters across and 81 centimeters deep. (Machinery Trader, 2018). This kind of machinery has undergone a revolution over the last 10 or 15 years. Integrated systems which incorporate hundreds of sensors allow the machinery's performance to be monitored exhaustively, with access to data banks managed by specialist software increasing productivity. Examples of these systems are: Caterpillar's MineStar®, IntelliMine®, koWA®, CENSE®, Contronic Monitoring System® and TRIPS® (Ataman and Golosinski, 2001). These innovations took place between the late 1990s and the first decade of the 2000s. Judging by the technological advances of the last 25 years, as well as those which are currently under development, a profound technological revolution in the mining sector is taking place.

In Mexico, over 90% of the production of the main metallic minerals is carried out by large transnational corporations which use this technology. Among these corporations are Goldcorp, Fresnillo plc, Minera Frisco, Peñoles, Agnico Eagle, and Pan American Silvery Grupo Mexico. Table 1 displays the results of ongoing research regarding the application of automatization to mining in Mexico. The data evidences the presence of this technology in all stages of the productive process.

Table 1. Examples of Automation, Monitoring, and Control Technologies Used in Different Stages of the Mining Process

Period	*Equipment*	*Brand*	*Origen*
Exploration	Vulcan, a common platform for geotechnic and engineering equipment	Maptek	Australia
Mineral extraction	Rig Control Systems (RCS), drill monitoring system.	Atlas CopCo	Sweden
Mine operation	Certiq, equipment supervision platform, a system which provides real-time performance reports on equipment for proactive maintenance.	Atlas CopCo	Sweden
	Mobilaris platform, a system which displays 3D information about subterranean mining processes in real time.	Atlas CopCo	Sweden
Grinding and milling	Automatic adjustment monitoring system (ASRI™) for crushers which monitors the size and load of material, enabling the equipment to later be optimized.	SANDVIK	Sweden
Flotation and leaching	ECS/ProcessExpert, a monitoring system for flotation and leaching systems which manipulates the actuators which monitor pulp, pulp Flow, ventilation, and reagent addition levels.	FLSmidth´s	Denmark – U.S.A
	QCX/RoboLabs, system for analyzing lab simples which uses automated equipment.	FLSmidth´s	Denmark – U.S.A.

Source: compiled by the author based on data obtained from: Maptek (2015); Mining & Construction (2014); Epiroc (2016); Mining & Civil Engineering (2018); Sandvik (s/f); and FLSmidth (2018a, 2018b).

Outcomes such as the increase in mineral process, the technological revolution, and legislative changes favorable to the entry of foreign capital have led to an increase in topsoil and subsoil exploitation in Mexico. By 2016, the Public Mining Registry had registered a cumulative total of 25,652 active mining concession titles which cover an area of 25.1 million hectares, around 11.3% of the national territory (SGM, 2017). This percentage represents an increase of 627.5% of the area of land being exploited since 2010, when the figure was 4 million hectares (SGM, 2001). The Mining Law states that “Any concession, allocation, or area that becomes incorporated into mining reserves must be referred to as a mining lot, stable throughout the range of its depth, supported by vertical planes, and have as its top face the ground surface on which the perimeters of the mine will be determined” (DOF, 2014).

In spite of the fact that mining continues to be one of the most productive sectors in the country, national investment levels have been low since 2012, when the sector recorded an all-time high value of $8,043 million USD. Throughout 2017, $4,302 million USD was invested, an increase of 14.7% from 2016. However, this value is still far below the high recorded in 2012 (CAMIMEX, 2018).

Foreign direct investment in mining has fluctuated heavily during recent years. It peaked at $5,265 billion USD in 2013, then diminished by 40% to $2,123 million USD the following year. Statistics from the Mexican Secretary of the Economy show that $718 million USD was invested in 2016, which is 86.4% lower than the amount invested in 2013, the year in which investment levels were highest (CAMIMEX, 2017c).

In spite of the reduced amount of national investment and foreign direct investment in mining over the past decade, after reviewing the annual percentages of investment in equipment made over the past decade by companies affiliated with CAMIMEX it becomes clear that these statistics are crucial, and that investment in equipment fluctuates between levels around one fifth of the total invested (CAMIMEX, 2009).

A second outcome of the technological revolution is concentration of capital. Large mining companies have replaced small and medium-sized ones to the extent that small and medium-sized mining companies’ share of the market is insignificant. In gold mining, for example, data for 2016 from CAMIMEX indicates that three companies, Fresnillo plc, Goldcorp, and Minera Frisco, account for 60% of gold production (CAMIMEX, 2017b). This stands in stark contrast to the national market share of medium-sized mining companies, which is just 1.03%, with small-scale mining companies accounting for just 0.01% of the national market (SGM, 2017).

Silver production is in a similar situation. CAMIMEX reports that, in 2016, 57% of silver production was concentrated in just five companies: Fresnillo plc, Goldcorp, Peñoles, First Majestic, and Pan American Silver. Fresnillo accounted for 26% of all silver production (CAMIMEX, 2017b). Medium-sized mining companies produced just 3.22% of silver produced in 2016, with small-scale mining companies accounting for just 0.25%.

4. CONCLUSIONS

One of the most definitive characteristics of mining development during the crash which started in the 20th century and continued until the present day is the so-called “mega-mining boom”, which uses automated and open-pit mining methods, where conditions permit. This period is also known as the period of “neo-extractivism”, a designation which relates mining practices with the neo-liberal policies of opening up of the economy to foreign investment which have facilitated the appropriation of enormous areas of land by large international-mining corporations, in particular in mineral-rich Latin American countries. This interpretation emphasizes government policy in Latin America, implemented as much by governments that are clearly free-market orientated as by governments which are more populist, albeit with reservations and differences.

Reviewing the distinct historical phases which mining in Mexico has passed through with an emphasis on technological change, in particular the most recent technological transformations in relation to fluctuations in international prices, gives rise to the hypothesis that mega-mining and open-pit mining are just as much products of material advances in the development of productive forces as they are the product of price increases and the application of government policy. Data gathered related to gold and silver mining supports this hypothesis.

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[1] Interviews were conducted with providers of: explosives, trailers and loading equipment, drilling rigs, flotation technology, laboratory equipment, software, and industry 4.0. Interviews were also conducted with specialists in: rock engineering, maintenance personal, area managers, and supervisors.

[2] Technology has always played in important role in economic history. Marx, for example, pointed out that: “what differentiates historical periods is not what work is done but with what methods it is done” (2010, p 218). Here, Marx is referring to economic stages which are radically different in terms of mode of production. However, the idea that technological change is crucially important is useful when attempting to delineate different periods of the same mode of production.

[3] Although, during the last 75 years of the 20th century and up to the present day, precious metals have not been predominantly used to produce currency. Instead, they have been mainly used for luxury products. The fact that gold, however, has maintained its importance as a store of value is crucial. This is demonstrated by the fact that gold repeatedly serves as safe haven during financial crisis, which in turn demonstrates that the function of metal as safe haven is a more important indicator than its assigned purpose in production. Currently, almost 30% of gold produced is used as a store of value in the form of ingots and coins (Coulson, 2011; Geocomunes, 2017).

[4] The reform relates specifically to fraction iv constitutional article 27 and allowed mercantile companies to become owners of rural land via the purchase of shares.

[5] As the parity between gold and silver began to fluctuate at the end of the 19th century due to the constant deprecation of silver, the value of the Mexican peso became very unstable, resulting in the government’s decision to switch to the gold standard.

[6] The modern versions are currently used in a wide range of areas, such as lead detection in paints.

[7] The main technological advances in mining during recent years are listed in Jébrak and Vaillancourt (2012).

[8] For an example, see, ETF (s/f) or Wirtgen GmbH (s/f).