Title	Proactive mining system in potosi silver mines : new information from re-evaluation of historical materials regarding the fifth viceroy toledo’ s various policies on environment
Author(s)	Anezaki, Shoji; Miyoshi, Emako
Citation	Osaka Human Sciences. 2016, 2, p. 171-197
Version Type	VoR
URL	https://doi.org/10.18910/56912
rights	
Note	

Osaka Human Sciences, **2**, 171-197
March 2016

PROACTIVE MINING SYSTEM IN POTOSI SILVER MINES: NEW INFORMATION FROM RE-EVALUATION OF HISTORICAL MATERIALS REGARDING THE FIFTH VICEROY TOLEDO'S VARIOUS POLICIES ON ENVIRONMENT

Shoji Anezaki*, Emako Miyoshi*

Abstract

In this paper, the proactive mining system introduced by the fifth viceroy, Francisco de Toledo (1569–1581) to the Potosi Silver Mine is clarified on the facts found in the historical documents. Main policies in Toledo's mining business are followings, the application of mercury-amalgamation to extract silver from ores, the construction of the hydraulic-powered system for silver-ore crashing with cascading uses, the recycle system included the extraction of silver from waste ores and collection mercury by pulp processing. Also in the Toledo's era, acceleration of developing Huancavelica mercury mine, and national monopolization and production control on mercury were established. And within Toledo's mining law, there were cautionary items for preventing the inhalation of mercury gas and the construction of hospitals for treatment. According to those items, the viceroy Toledo may be prominent organizer for business but because these were not technically perfect, environmental damages referred to now as mine pollution started from the colonial period and continued until modern-day period. This pollution can be found in Potosi's air, water, and soil. The history of Potosi mine can't be described leaving out the viceroy Toledo.

Key words: Potosi silver mine, Viceroy Francisco de Toledo, mercury amalgamation, hydraulic powered system, environmental pollution

---

This article is the English translation of the original one "Shoji ANEZAKI and Emako MIYOSHI (2014). Proactive mining system in Potosi silver mines: New information from re-evaluation of historical materials regarding the fifth Viceroy Toledo's various policies on environment. *Journal of the Historical Study Group of Mining and Metallurgy*, **68**, 63–82 (in Japanese)". The publication of its English translation has been permitted by the Historical Study Group of Mining and Metallurgy of Japan.
* Graduate School of Human Sciences, Osaka University, 1-2, Yamadaoka, Suita, Osaka 565-0871, Japan

1. Introduction: Summarized history of the Potosi silver mines and research objectives

Upon entering the 21st century, underground resource consumption is on a steady rise due to remarkable progress of scientific technology and globalization.

On the other hand, there is heightened focus on recycling terrestrial resources (also known as artificial or urban mines) in aiming to develop a recycling-oriented society.

With respect to the mining industry, though the development of sustainable mines[1)2)] from a global environmental standpoint is a recent concept, mine pollution is a persistent constant around the world[3)]. In general, the severity of mine pollution is defined by the size of the business, the development speed, or the mining period.

From a historical viewpoint, the silver mining business saw a golden age during Europe and its colonies' pre-industrial era. It is useful, then, to study the mining business of the time from the point of view of sustainability, which is a universal idea. It is possible to find traces of sustainability innovation from this era that may benefit the modern world. As an example, there are existing disquisitions[4)] and public documents[5)] concerning the recycling-oriented society of the Iwami Silver Mine, which was already known over the world by the 16th century.

This paper focuses on gold and silver mines in Spanish colonies in South and Central America after the late 16th century, the same era as described above. This era is especially notable for the discovery of silver mines and their rapid development, which helped fiscal reconstruction of the Spanish monarchy. It is also notable for its strong impact on the Price Revolution due to the expansion of trade and globalized economy, even it was not the main cause[6)7)]. This study primarily focuses on the Potosi silver mine (located in present-day Bolivia) and aims to reanalyze various measures and policies from perspective of sustainable mine development[1)2)] in order to obtain new information.

In the Viceroyalty of Peru, output from the Potosi silver mines, discovered in 1545, underwent rapid growth during the reign of its fifth viceroy, Francisco de Toledo (1569–1581, hereinafter referred to as "Viceroy Toledo"). The reason for this is not only the application of the mercury amalgam method, but also the many geological and cultural advantages in the area. However, the author deduces that the biggest element to this growth was Viceroy Toledo's outstanding organization skills as a businessman, as well as his systematic and strategic sense of judgment and executive actions.

Figure 1 shows the transition in output of major silver producing countries and the Potosi silver mines from the late 15th century to 17th century[4)7)]. The Potosi silver mine saw rapid growth in silver production during the late 16th century, and maintained its record status for over 200 years. The rapid growth from the 1570s to the 1580s was achieved during the reign of the fifth Viceroy Toledo (1569–1581).

Viceroy Toledo's devastation of the Andes society through his mining business is a grave historical reality. The negative impression this left may be a reason why so few evaluations and

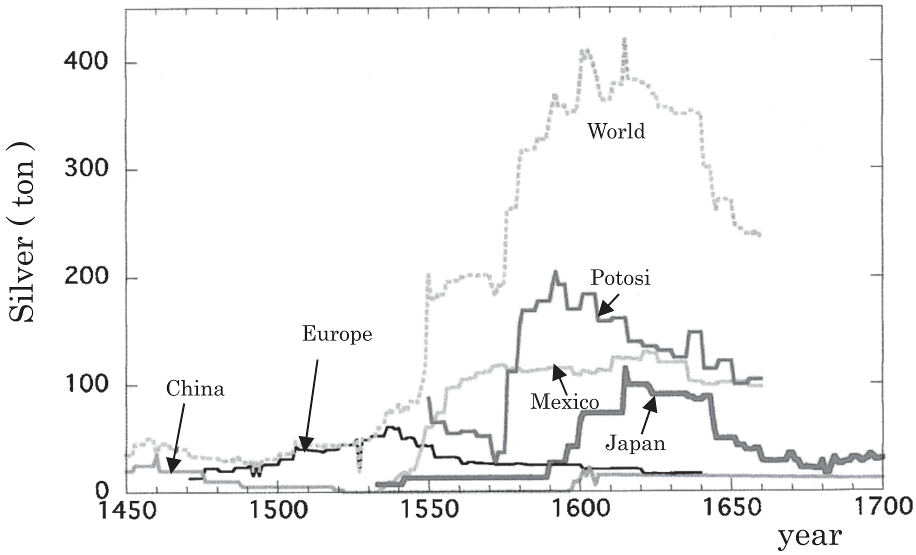

FIGURE 1.
The changes in silver output of major silver producing countries from the 15th century to the 17th century[4)7)]

studies exist that focus on Viceroy Toledo as a businessperson.

The author, as well as others, has researched the technical changes of the mercury amalgamation method that was introduced to the Potosi silver mines as well as the facts regarding mercury contamination, and estimated the amount of accumulated mercury in all Spanish colonies[8)9)]. Additionally, during the process, we focused on a power dam collapsing accident that occurred in 1626 in the Potosi mines, and examined the facts regarding past civil engineering technology, flood damage, and mercury diffusion based on historic records[10)11)].

This study, based on the aforementioned results, focuses on the importance of efficient processes that Viceroy Toledo, who carried out the massive revolution on the Potosi silver business despite having no concept regarding systemization of the mining industry in the mid-16th century, accomplished through systematic ideas, as well as the collection of waste, etc. in modern resources recycling,. It found facts related to the above in historical documents and then attempted to reassess his achievements from the point of view of modern recycling-oriented social theories and sustainability science. This paper focuses on analyzing schematics and records from the time period, and documentation within those that were close to the original text.

There are 4 main items of research, which are as follows.

(1) Summary of Viceroy Toledo's mining business and policies
(2) Analysis and explanation of bird's-eye diagrams of the Imperial capital Potosi as well as process diagrams of the refinery
(3) Geological examination and mining technologies of the Potosi mines
(4) Policy from the point of view of sustainable mine development, such as tailing and pulp

recycling, and its influence on today

Finally, this paper looked into aspects of Viceroy Toledo himself, the man who was able to accomplish his business.

2. Summary of Viceroy Toledo's mining business and policies

2.1. The Peru style mercury amalgamation method which led Viceroy Toledo to succeed in the mining business

Since its discovery, the Potosi mines had been extracting silver from outcrops of rich ore through a native technique known as the Guaira Method (a type of Pb dissolution method). In 1569, during Viceroy Toledo's post at the mines, rich ores began to decrease in number and underground mining was gaining popularity. This led to a slump in the output from the Guaira method. At the same time, an exorbitant amount of scrap and obsolete ore was piled around the mine. These contained substantial amounts of silver, but could not be refined by the Guaira method, and were thus abandoned. They were described at the time as low-grade ore or scrap ore (desmontes)[12)].

In 1555, at the Pachuca mines in Nueva España (a Central American region centered around modern-day Mexico), Bartolome de Medina (1506–1575) successfully implemented a silver ore refining method using the mercury amalgam method (the Patio Method), and applications of it spread widely[13)].

There are records that indicate that the Patio method was introduced and tested in Peru, but said method had not become industrialized. In 1572, Viceroy Toledo secretly started experimenting using a new method brought over by Fernandez de Velasco, an experienced worker at Pachuca mine. The successful results from these experimentations pushed him to implement various policies which will be described later. This new method was made secret and no records of them are left. But records from the 1640s disclosed that the method was a reaction promoting method (Cajones), involving mixing and heating in box-shaped reaction basins (cajones)[14)]. The Cajones method made it possible to extract tremendous amounts of silver from the scrap ores after a 5 year period, which became a source of funds to carry out policies[15)].

Figure 1 shows the changes in silver output around this era. The rapid growth from 1572 to the 1590s is clearly Viceroy Toledo's effect on the mining business.

2.2. Main policies in Viceroy Toledo's mining business

Viceroy Toledo's policies after attaining basic refining skills are summarized below.

(1) Structuring a hydraulic-powered system

It is necessary to improve ore grindability from the perspective of kinetics. In order to improve grind efficiency using a water wheel grinder, a comprehensive hydraulic-powered system was constructed. Six dams (32 dams by 1621, with a gross reservoir capacity of 6–10 million m^3)[16] were constructed at Caricari massif valley on the east side of the Potosi mines, and a waterway for grinders (La Ribera), a waterway for selecting ore by flushing, and a domestic water route (Zanja) were also constructed. The refinery arrangement along La Ribera made it possible to adopt a cascading system for utilizing limited water supply. As a result, this made it possible to collect tailing and pulp after mineral dressing, as well as collect and recycle of mercury spillage[12][17].

(2) Implementation of the forced labor system for natives (Mita)

Underground mining had already become popular among mercury and silver mining, and ore transport work was becoming a limiting process. Because only natives could conduct labor-intensive work at high altitudes of 4000 meters and higher, an Incan era rotational labor service system (Mita) was combined with the colonial policy of forced labor to implement a multilayered system known as the Mita system, which gathered laborers from a wide range of regions. This system caused numerous casualties and received much criticism, though it continued until the beginning of the 19th century[18].

(3) National monopolization and production control on mercury

Mercury as raw material was supplied from the Huancavelica mercury mine, discovered in 1563 within the Viceroyalty of Peru. It was designated as a royal monopolized mine and its production and income were controlled. Because the yield here was linked so intimately with silver production in Potosi, it became known as the "marriage of 2 mines". Figure 2 shows

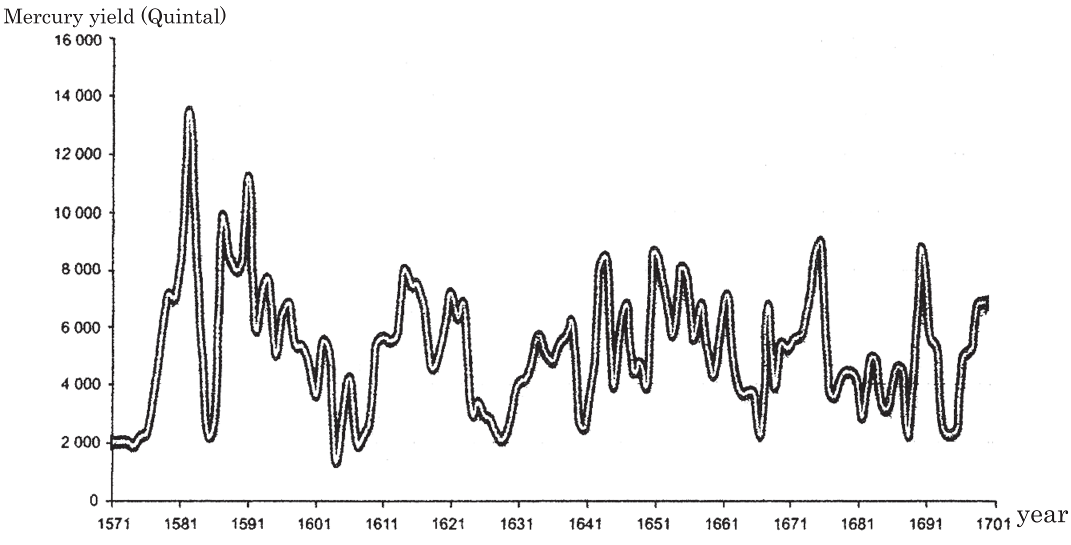

FIGURE 2.
The changes in mercury yield at the Huancavelica mercury mines[19]

changes in the mercury yield at the Huancavelica mines over time[19]. That amount was balanced with silver yields over an extended period of time, and amounts in excess were supplied to Mexico most likely in order to balance supply and demand. Officially, in 1572, the Royal Financial Bureau (Casa de la Moneda, Cajas de Reales), was established at Potosi[20][21].

(4) Viceroy Toledo's mining law

The mining law was put in effect for both mines, and the mine owner's responsibilities were clarified. Within this law, though practice may not have been as it was written, there were cautionary items for preventing the inhalation of mercury gas while on duty regarding mercury handling operations. Furthermore, the construction of hospitals for treatment, as well as the number of days and amount of compensation to be given for treatment expenses was also legislated within this law[22].

Aside from this, the following facts are assumed to be special conditions which led Viceroy Toledo to success in the mining industry.

1) The altitude of the Potosi mines and Huancavelica mines are over 4000 m. In this extremely elevated mountainous region (dry Puma), there were natives who had formed cultural spheres in the area. There were also llamas, which are animals for cargo work, and an area for daily commodity procurement established through vertical control which existed since the Incan era[18][23].

2) Hard work was able to be overcome thanks to the existence of activating foods (coca) that were inherited from the natives. Furthermore, there was an abundance of alpine plants (icho, a plant in the Gramineae family), which were used both as plants for making housing and for feeding llamas. These plants were suitable as fuel in low-temperature conditions, and their two-year growing span made crop rotation possible[24].

3) There were good geological features. The Potosi mines had a massif that was nearly 5000 meters high on their east side, and their gorge which has existed since the Ice Age contains natural ponds. It was possible to build a huge group of dams through damming and connecting these bodies of water. Furthermore, there were natural rivers with rapid currents that ran through the city of Potosi on an incline, allowing large-scale cascade-type water wheels to be established that utilized La Ribera waterways. The waterways gathered to the Rio Pilcomayo, and eventually flowed into the Atlantic.

3. Analysis of the mining city structure from diagrams of the imperial capital Potosi

3.1. Comparison between bird's-eye diagram of the imperial capital and modern aerial photography

Figure 3 is a bird's-eye diagram of Potosi in the mid-18th century, drawn by Gaspar (Gasper Miguel de Berrío, 1706–1762) in 1758[25]. For purposes of comparison, Figure 4 shows an example of aerial photo of modern-day Potosi.

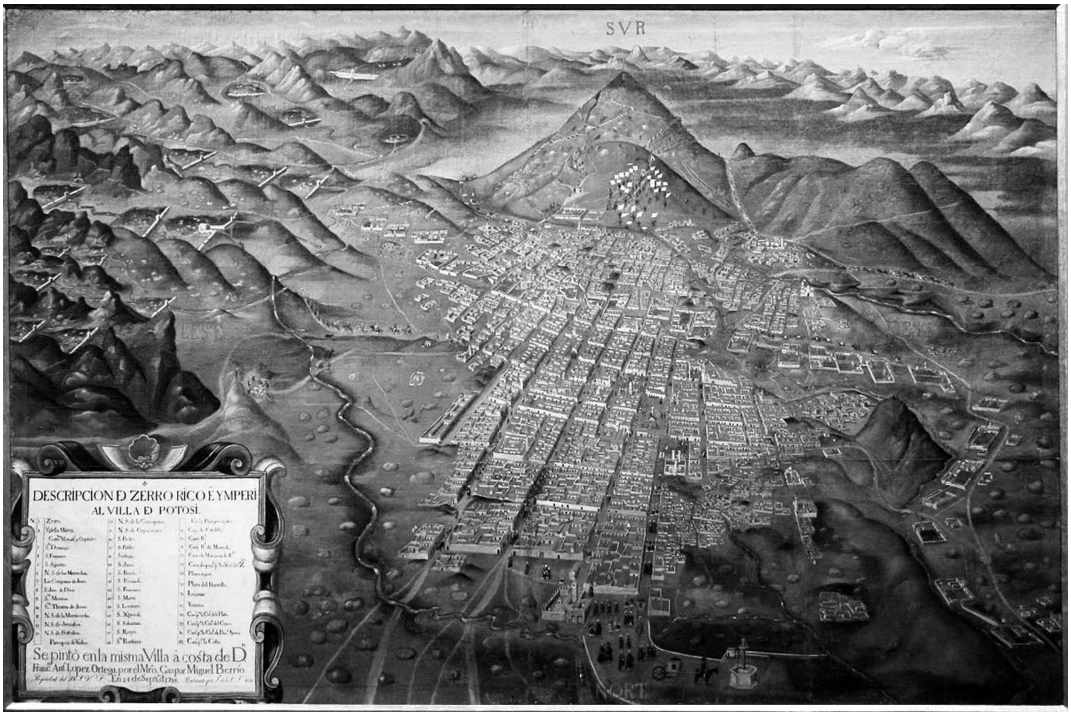

FIGURE 3.
Bird's-eye diagram of the imperial capital Potosi (Gaspar 1758)[25)]

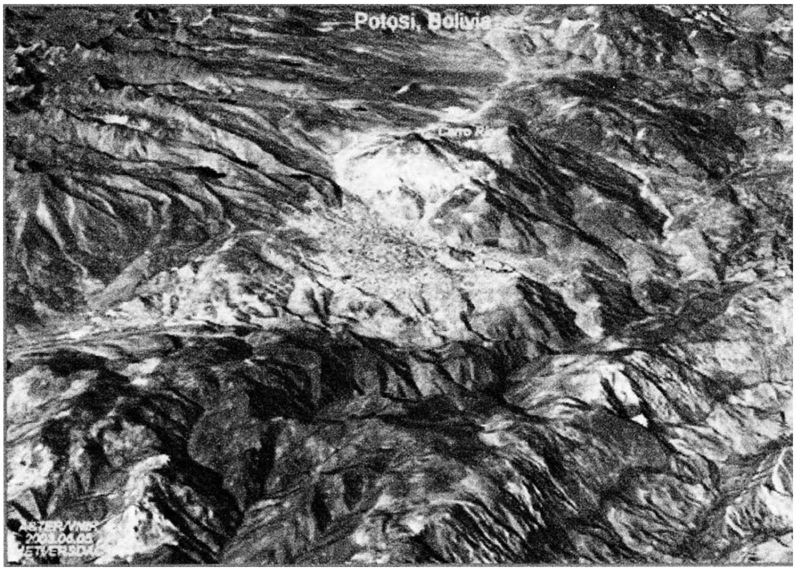

FIGURE 4.
Aerial photo of the modern-day Potosi mine area

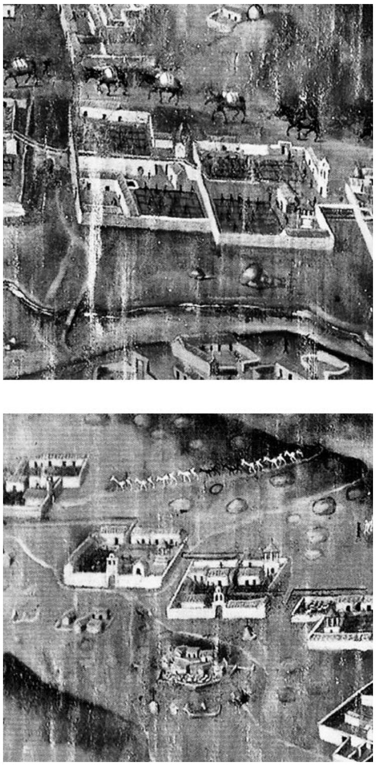

FIGURE 5.
Detailed diagram of hydraulic-powered sections in Gaspar's diagram[25)]

Looking at the entire structure, the Potosi silver mines (4820 m) faces a city that spreads in front them, and are located to the upper left (Southeast) by the Caricari massif (as high as 5000 meters), which is connected to groups of dams at its gorge (18 dams are shown in this figure). The waterway for water wheels, La Ribera, runs through the west side of the groups of dams, from the top of urban city area to its center, and there are refineries along this waterway. These sections are enlarged and shown in detail in Figure 5[25)]. In this figure, waterways are depicted separately for the refinery (ingenious, or azogeros) and the mine crushing factory (haciendas, or molineros). In each case, water is shown to be used in the cascading style.

Looking at the entire structure, the Potosi silver mines (4820 m) faces a city that spreads in front them, and are located to the upper left (Southeast) by the Caricari massif (as high as 5000 meters), which is connected to groups of dams at its gorge (18 dams are shown in this figure). The waterway for water wheels, La Ribera, runs through the west side of the groups of dams, from the top of urban city area to its center, and there are refineries along this waterway. These sections are enlarged and shown in detail in Figure 5[25)]. In this figure, waterways are depicted separately for the refinery (ingenious, or azogeros) and the mine crushing factory (haciendas, or molineros). In each case, water is shown to be used in the cascading style.

The center of Potosi city is 2826.7 meters above sea level. Its Central Square (Plaza Principal) is 2900 meters above sea level, and San Clemente Temple is lower at 2700 meters. As Figure 4 indicates, there is an extremely steep incline from the city entrance of La Ribera down to the northwest edge[26)]. This leads to the supposition that the incline contributed to the fact that each refinery was able to secure elevation differences.

According to T.S. Reynolds[16)], the steepest incline in Potosi was 594 m/4.8 km. Additionally, in 1575, there were 74 crushing machines that utilized water wheels alongside the riverbank in 48 factories[12)]. If these machines had been lined in a row, each machine would have had a drop in incline of approximately 8 meters.

Meanwhile, as detailed information regarding diagrams and dimensions of crushing machines, the following 3 types of documents are given as examples. However, there many other records left on Cronista[27)].

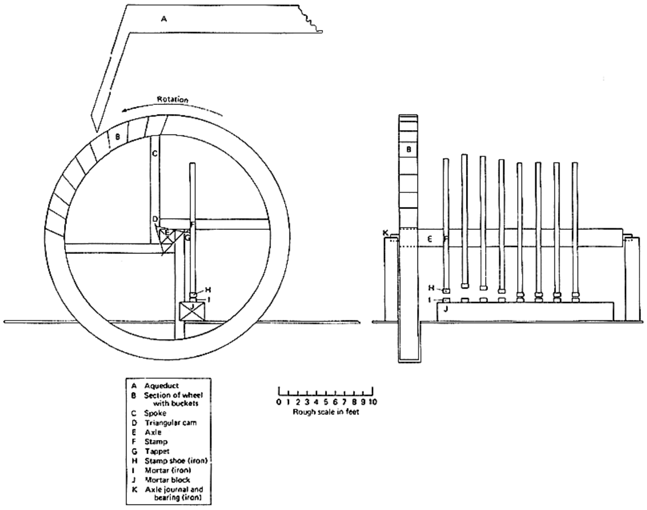

FIGURE 6.
Diagram of a one-headed water wheel with eight pistons[15)]

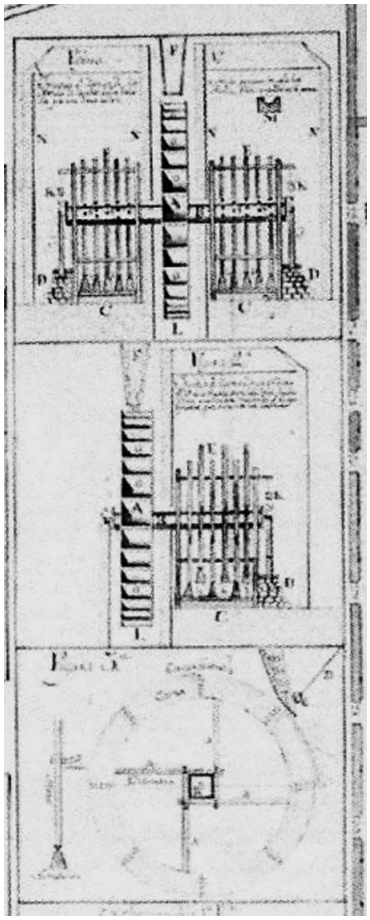

FIGURE 7.
Diagram of a one-headed wheel with 6 pistons and two-headed wheel with 10 pistons[25)]

1) There is a drop of 8.3 to 11.1 meters, and the diameter of the one-headed water wheel was 6.1 meters, 7.2 meters for two-headed water wheels. The diameter of the piston was approximately 10.5 centimeters, and its length was 2.6 to 2.9 meters[27)]. Note that the paving stone on the concave surface below the piston was denoted as 'cabeza', which means "head".
2) Figure 6 shows the one head type. The water wheel diameter was 43 feet, which is approximately 12.9 meters[15)].
3) Figure 7 is a diagram of both the one-headed and two-headed types, but the detailed dimensions are unreadable[25)]. However, according to Capoche (1548–1624)[28)], the length of the wooden material for the core shaft was 21 pies (5.88 m), and the diameter was 2 pies (56 cm). Thus, it has been estimated from this ratio of the core shaft that the water wheel in Figure 7 is 6 to 8 meters in diameter.

From the information listed above, research deduces that the maximum drop was almost 13 meters, and the average drop was around 8 to 10 meters.

Figure 5, the detailed diagram of each part in Figure 3, depicts a scenario in which the drop in incline is secured, and each of the refineries and mine crushing factories use the water from the waterway in the cascading style.

Such examples of large-scale complex utilization of hydraulic power had already existed in mining areas in Harz, Germany. The system in Potosi was almost the same in scale, but is distinct in that it utilizes hydraulic power in the cascading style[16)]. It is believed that these features were an advantage when conducting pulp processing after the selection process of ores post-washing, as well as for pulp collection for recycling[29].

3.2. Work process system analyzed from the diagram of Arzans' refinery (Figure 8)

In Arzans' (1662–1736) report, Figure 8 has been inserted into the description for 1577[18]. Taking into account the fact that this report was written during his lifetime, the work scenes that are depicted in the diagram is likely that of the beginning of the 18th century, approximately 150 years in the future. However, the contents agree with those of Capoche (1585)[28] and Acosta (1584)[12], which implies that the contents and processes of the work has not changed considerably since the late 16th century.

The following will describe a concrete image of the work process through analysis of the memos on each operation drawing in Figure 8.

This diagram is believed to be a depiction of the external appearance of one refinery (ingenio). The refinery is surrounded by walls and buildings, and a waterway (La Ribera) runs around half of the premises. A portion of the crushing machines is outside of the wall, but this is believed to be this way to secure elevation differences and keep the two water wheels moving. To exit and enter the refinery, the second service entrance to the upper part is for ore reception, and the first service entrance to the lower part is believed to be the main entrance. By the second service entrance, there were observation posts for ore reception, watch houses, and management rooms

Figure 8.
Work process diagram of the refinery (ingenio) drawn by Arzans[17]

for refinery materials with a reception window. Additionally, by the main entrance side, there was housing for the refinery owner (azoguero), a chapel, and a storage warehouse for silver and mercury.

Regarding the facilities, there are two waterwheel-powered crushing machines (the one is one-headed machine with five pistons situated outdoors, the other is two-headed type with twelve pistons situated indoors), and two pieces of sieve apparatus made of net near the central area. There are four heating furnaces (buitrón). Each furnace contains six to nine reaction tanks (cajon, generally referred to as cajones). Crushed ore is weighed and inserted into the cajones, then kneaded on foot by several people (repaso). Preparations are conducted in one of the four heating furnaces (bottom center). Here, there is a scale (topo, weighting 2 arrobas, or approximately 23 kilograms). Kneading mostly likely happens in the remaining three heating furnaces. Each cajon yields 1 quintal of ore (approximately 46 kilograms). On the bottom left, there is a hut (ramada) where each ore in a cajones is analyzed. Based on the results of the analysis, the amount of mercury seems to have been calculated[28)].

A notably unique feature to mention here is the treatment process of negrillo (black ore), which was abundant at the time. Only the negrillo are gathered at the bottom left and fired in roasting furnaces (ex. desulfurization from sulfide ores), and dried and cooled at the left of the first service entrance. Then they were mixed and refined in the special heating furnace at the top. It is believed that the crushing machine situated outside were only for the negrillo.

Regarding treatment after refining, a waterway that cuts across the center is used. The first stage of the washing is done upstream, and uses two large barrels (tina). The second stage uses two smaller barrels for the washing to extract rough amalgam (pella). The tailing consists of “lamas”, which are separated at the first stage, and “relaves”, which appear at the second stage. Though they are not depicted in this diagram, it is believed that these tailings, especially lamas, were gathered in small pond (pozo), and analyzed to later be collected and refined[11)]. The rough amalgam (pella) is separated into silver amalgam (piña) and mercury at the separation hut (ramada) located in the center left. At the bottom left, there is a storage warehouse (almacenes) for silver and mercury.

There is no mention of the total area of the refinery, but as described above, it is said that each refinery would have required at least 1 hectare to store all of the necessary facilities[25)].

The total number of the workforce as depicted is sixty. A majority of these workers, 31, worked on the cajon, and 12 of them worked at the material reception section. The diagram depicts a llama group of 13 entering the refinery. Inside of the property, there are two workers for mine crushing, but nobody at the crushing machine outside the premises. Of those remaining, there are six workers for mine selection and three workers waiting to be assigned somewhere. Regarding the distribution of the workforce, according to the 1603 numeric data for native allocation in all of Potosi, records show that there were 4000 workers (minga) who were assigned to ingenious[30)]. Therefore, after dividing the number of workers by the number of ingenios, which was 132[12], the math indicated that approximately 30 workers were assigned to each refinery. This calculation is almost an exact match to the 31 in Arzans's diagram[25]. By comparing these estimation results with Acosta[12] and Capoche[28] records, the work process in Arzans's diagram can be considered an average ingenio's process in the late16th century to the beginning of the 18th century.

On the other hand, there are sections in a diagram that dates to around 1584 (Figure 9)[31] that show some slight differences from Arzans's drawing in 1736. One of these differences is that no workers for mixing are depicted in Figure 9, despite the depiction of 14 cajones as reaction tanks. This difference has been attributed to differences in timing between mixing-heating-ripening works[14]. Furthermore, in the latter, there are piled lamas that have been washed and removed from the barrels within the premises, and a depiction of a collection furnace for mercury in the center right of the diagram (the section with the depiction of smoke). This suggests that mercury collection from pulp was part of the process from the beginning.

Moreover, the following can be pointed out as a reason why there is a difference between what was depicted in 1736 and what was depicted in the Toledo era. In 1621, a hydraulic-powered network was completed, which helped to increase water consumption in the Arzans era. This is believed to have allowed waterways to be introduced inside property. It has also been inferred that technology to roast negrillo in advance was also introduced at this time[17]. Additionally, according to Alvaro Alonso Barba (1569–1662)[32], there were varieties of heating furnace

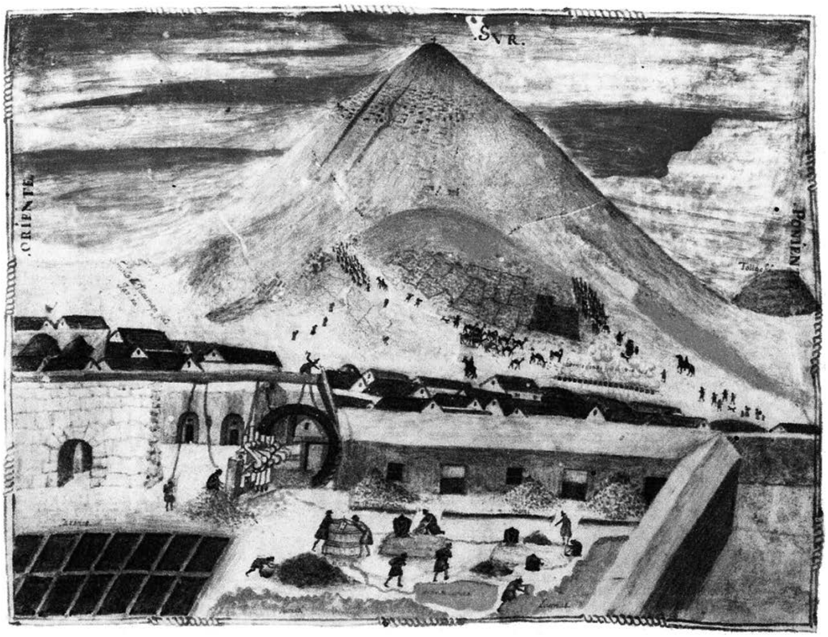

FIGURE 9.
Scenery depicting refineries in Potosi in 1584 (watercolor painting)[31]

types depending on the purposes or the materials. Thus, it can be read from these details that developments were made to further innovation thanks to the development of fuel and exhaust methods, etc., with respect to handling mercury ore and silver ore, whether these ores will be in solid or powder form, and whether they will be roasted (desulfurized) or calcinated (decarbonized).

Generally speaking, because the refining industry is also a conglomeration of the handicraft industry, such as the lumber industry, brick grinding, crucible manufacturing, plaster processing and quarrying. By attempting various new measures and combining them with skilled labor to make these improvements, it can be inferred that material supplies, distribution bases, and business regions were developed, transforming the local community[33)34)].

4. Geological characteristics of the Potosi mines, and silver ore and mining technology

4.1. Description of silver ore grades in the Potosi mines

Regarding the categories and grades for silver ore, Capoche[28)] and Acosta[12)35)], in the late 16th century, described it as the following. The silver ore that natives supplied using the Guaira Method was called tacana, and the silver yield per one quintal was 30 to 50 pesos. However, Acosta himself had heard of yield of 200 to 250 pesos. Such high-grade ores contained a high percentage of lead (Pb) and sulfur (S), and were not suitable for refining by mercury (amalgamation). On the other hand, it is believed that that desmonte (tailing, waste ore, or poor ore) contained low percentages of lead (Pb) and sulfur (S), and were easily amalgamated for silver.

Arzans[17)] described that many ores were distinguished by their difference in detailed color tone, etc. but that it took years of experience to be able to ascertain the grade. Furthermore, Percy[36)] organized Arzans's description and divided into 2 categories. One category included a metallic silver and a silver halide known as pacos. Pacos is a compound of chlorine (Cl), boron (B), iodine (I), and silver. When combined with pyrite (iron sulfide FeS_2) which contains iron (Fe) and copper (Cu), the resulting compound is known as mulatos. Pacos is also known as "metal calido" (hot ore) and is fit for amalgamation. The second category is negrillos. Negrillos contain argentite (Ag_2S), and silver sulfides containing antimony (Sb), and arsenic (As) (the former is pyrargyrite and the latter is proustite). If there is an abundance of the aforementioned pyrite, it becomes necessary to roast the ore before amalgamation. The second category is denoted as "metal frío" (cold ore). These negrillos are processed at the left line on Figure 8 by Arzans.

According to Percy, the ore grade was 4.5% in 1574, and dropped to 0.04% by the beginning of the 19th century. According to Capoche[28)], upon designating the refining limit at somewhere between 0.1% and 1.15%, silver analysis values were set as baselines for mercury dosage criterion.

Recently, Bargalló[37)] reported that the ore grade in Potosi was 40 to 45% in 1545, 4 to 4.5%

in 1574, 0.75% in 1607, and 0.27% at the end of 18th century (percentages converted by the author). From this, it can be inferred that the grade of ore at the time of vein discovery was extremely high: as high as 40 to 50% in silver content. However, after Viceroy Toledo's era, the ore grade lowered and underground mining became more mainstream. After the 17th century, it is believed that the ore grade fell even lower, which resulted in the situation as described above.

4.2. Geological investigation of the Potosi mines

Cieza de Leon (1518–1554)[38] found the following 5 vein outcroppings in the Potosi silver mines in 1549. Figure 10 depicts the veins (veta) at the time. Here, the paper includes 5 supplementary notes.

1) veta Rica; discovered by Natives in Porco, Gualpa. This vein is usually referred to as La Rica.
2) veta de Centino; discovered by the Ganca, neighbors of the Gualpa. Registered and pile driven by master Villaroél on April 21st, 1545.
3) veta del Estaño; discovered after Centino. A vein containing tin, or estaño.
4) veta de Mendieta; Registered on August 31st, 1545.
5) veta de oñate; No records found aside from its name.

In the report in 1584, Acosta[12)35] reported that the veins above appeared on the mountain surface on the east side of Potosi, and describes 1) to 3), as follows.

1) La Rica; A large metal that protruded outwards like a rock, due to weathering. It was as high as the length of a spear, and protruded out of the surface of the earth like a cockscomb. The

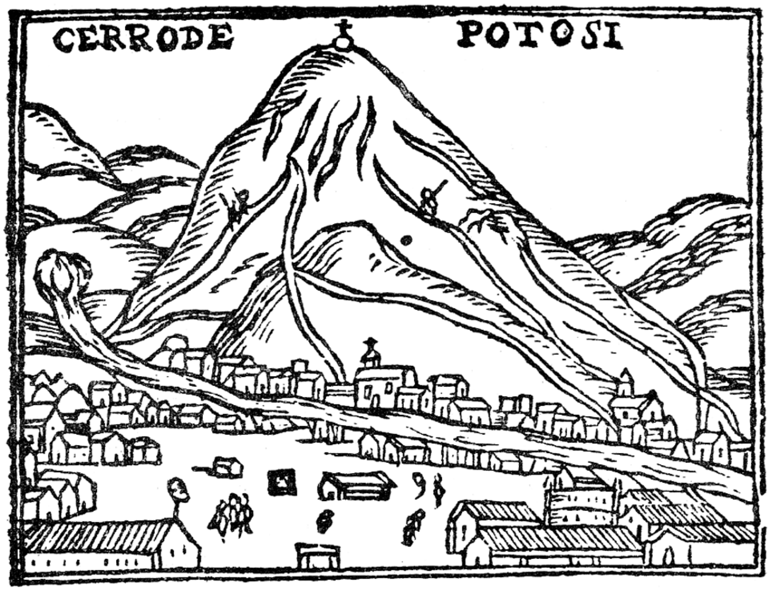

FIGURE 10.
Scenery in Potosi before adoption of the amalgamation method[38]

length of the vein was 300 pies (84 meters), the width was 13 pies (3.6 meters), and the depth was 50 to 60 estados (100 meters to 120 meters). The silver content was approximately 50%.

2) Centino; Though it was hard to mine, it was ore rich in silver.
3) veta de Estaño; As hard as flint, and extremely difficult to mine. However, the ore is rich in silver.

Besides the above, Acosta reported upon the shape of the mountains in Potosi. He described that the mountains were 1624 varas (1.36 kilometers) from the foothill to the summit, and that the foothill was almost in the shape of a circle whose diameter was approximately 1 legua (5.6 kilometers). The calculation for the angle of incline based on these descriptions is approximately 49 degrees, which is fairly steep. However, it has been reported that horses were able to climb these inclines.

Guaina Potosi ("Young Potosi") is located on the northern side of the Potosi silver mines (the urban region). Acosta[12)] described the characteristics of the silver ore of both mines as follows: the Potosi silver mine was vetas fijas, meaning "fixed layers of large-scale veins", and Guaina Potosí was suertas, meaning "flaky ores containing little but high-grade silver."

Next, based on recent geological studies on Potosi mines, the paper will inspect the aforementioned description made by Cronista.

Firstly, Figure 11 depicts the geological cross-section of the Potosi mines[39)] from the side opposite to the one depicted in Figure 10. According to Dr. Mariko, the vein runs mostly in the northern and southern direction[40)].

From what is indicated in Figure 11, the geological appearance of Potosi, the area is comprised of an Ordovician slate and a dacitec tuff breccia Pailabiri foundation layer. The lower region is pipe-shaped, and the upper region is made of a funnel-shaped penetrating dacite that was heavily

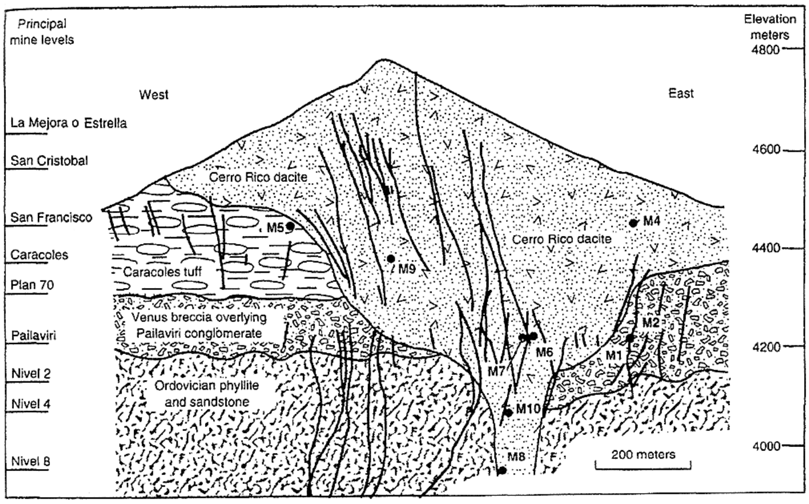

FIGURE 11.
The geological cross-section of the Potosi mines[39)]

changed by hydrothermal alteration. The epithermal magma penetrates in a north-south direction into the bedrock, which forms the vein[40].

Characteristics of the metal composition of the vein can be attributed to orogenesis. The Pacific Rim metallogenic planetary belt is comprised of the enormous Andes batholith (approximately 6000 kilometers in length), and it is a penetrative deposit zone. In metallurgy, it is divided into the outer zone of the deposit formation zone group (Sn, W, Sb, Bi), and the inner zone at the Pacific Ocean side, (Cu, Au, Ag, Pb, Zn). The Potosi silver mines are within a tin formation zone in the outer zone, but are also a shallow structure epithermal tin deposit that belongs to the young tin deposit and tin-silver deposit formation zone of the early Paleogene period. As described below in 5.4, these mines can also be considered a tin mine[27].

According to Brading[21], the initially hot water magma in the Pacific Rim metallogenic belt was low-grade sulfide. This separated into natural silver and oxide silver at the surface through weathering, and became a soft reddish ore (colorados, or pacos). Then, long-term rainfall separated then out into the water table, and reacted with early ores to form secondary concentrated sulfide. This took on a form which was hard and black, called negrillos. The silver concentration was as high as that of the aforementioned pacos. Within this mid-term rich ore, there was an abundant low-grade primary sulfide layer. The conical shape of the Potosi mines facilitated oxidation, which promoted the formation of a layer containing oxides and chlorides. The vein reached 250 yards (approximately 230 meters) in depth. The middle layer contains high-grade chlorides within, and forms a deposit with a vein containing many varieties of ingredients.

When drawing comparisons with Acosta's record, the silver ore that the natives had applied the Guaira method in Figure 12 was a rich ore (cacilla or tacana, with an abundance of Pb). They had also incorporated galena (soroche) to the smelting process[12]. After this, the ores were brought to another location as indicated by the smaller furnaces in Figure 13 to be blown several

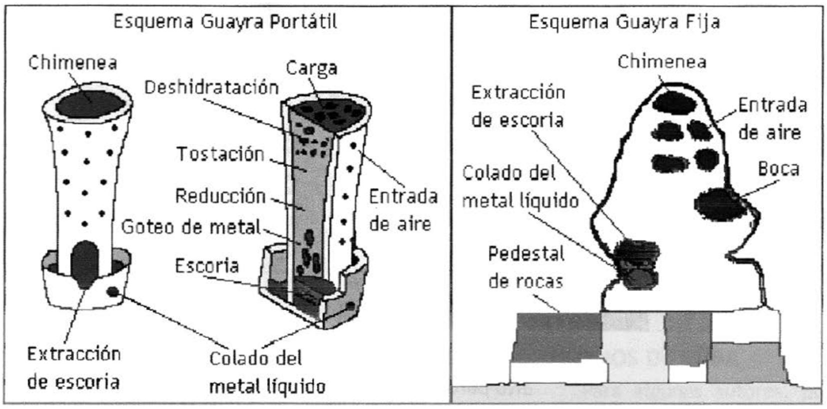

FIGURE 12.
Varieties in the Guaira method among natives[42]
(Carrying-in style and stationary style)

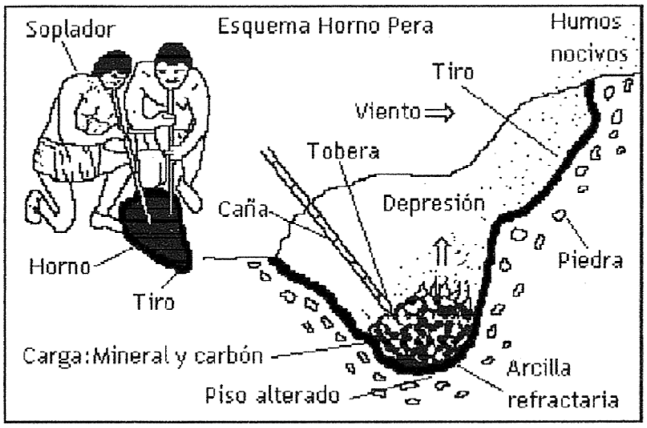

FIGURE 13.
Blowing method for refining devised by the natives[42)]

times with Pb in order to improve purity. It can be said, then, that they had devised a unique two-step refining method that was similar to the German Seiger method[42)]. It is believed that the reason why the ore in veta de Centino and veta de Estaño was hard was its high Pb content, which was suited for the Guaira method.

4.3. Mining technology at the Potosi mines

The mining method at the Potosi mines was initially utilized at the outcrops detailed in Figure 10. Eventually, the mines were excavated further downwards and included the surrounding areas. By the 1560s, they reached 200 to 250 yards (approximately 180 to 230 meters) in depth. It was during this time that the first adit (sacavon), Nicolas de Benino (320 yards deep from the apex, 250 yards in length), was constructed. At the time, 5 other adits had been excavated[28)]. The dimension of these adits was six feet high by five feet wide, wherein two people could walk side by side. In following years, more adits were built under the leadership of the fifteenth Viceroy, and a 400 yard adit was constructed by 1640.

To modernize mining, it was necessary to prepare underground mining technology, especially shafts and adits. Thus, after the slump period in silver mining after the mid-17th century, as part of the Bourbon Dynasty's reconstruction projects, a mine shaft six feet vertically and horizontally and 2200 feet in length completed in the late 18th century (1789 to 1810). This restored competitiveness[25)]. Figure 14[43)] shows the cross-section of a shaft and adit that was drawn in 1779. This does not depict the last completed shaft, but 5 locations have been indicated (B, C, F, O, and P). The consistency between Figure 11 and Figure 14 is a future task to investigate.

The Potosi mines are geologically a layer of sandstone and waste conglomerate, and their conical shape provide smooth drainage. On the other hand, there were frequent cases of cave-in accidents[17)].

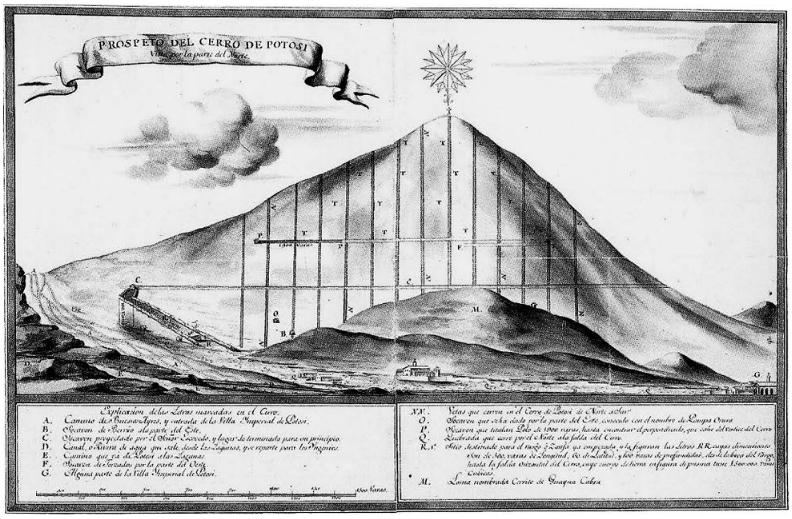

FIGURE 14.
The cross-section of the Potosi mine shafts as of 1779[43)]

5. Various policies concerning sustainability under Viceroy Toledo's leadership[29)]

5.1. Collection of silver from waste ores (waste ore, scrap ore, or slag) pre-appointment of Toledo

As described above, the most important policy that Felipe the second, the King of Spain (1556–1598), assigned to Viceroy Toledo was restore the Royal finances by developing the silver mines. Within this assignment, Felipe the second directly ordered Viceroy Toledo to collect silver from the abandoned desmontes (waste ore in and outside of the mineshafts) using the mercury amalgamation method[14)].

Since its founding in 1545, the Potosi silver mines silver production had relied on the natives' Guaira method. As mentioned above, this method was suitable for rich ores found in outcrop. By the late 1560s the grade of the ores had dropped, and while underground mining developed, productivity decreased. By early 1570, the Guaira method had hit a slump. Because natives were only selecting and using rich ores, waste ores were piled in mineshafts and around shaft entrances[12)28)]. Among the waste, the authors infer that slags from the Guaira method were also included[29)].

Meanwhile, the mercury amalgamation method was successfully used in industry by the mine owner residing in Pachuca, Mexico, named Bartolomé de Medina (1504–1575) as a silver refining method (Patio)[13)]. This method was suitable for lower-grade ores that were not targeted by the natives, and was expected to be a processing method that could be applied to poorer ores. A mercury mine was founded in Peru in 1563, at Huancavelica, which cast new expectations on the mercury amalgamation method and led to several attempts to perform it[24)].

There is a considerable difference in geography, climate, atmospheric pressure, oxygen concentration, temperature, and amount of rainfall between the Mexican Plateau (approximately 2000 m) where the Pachuca mines are located and Upper Peru (approximately 4000 m) where the Potosi mines are located. Furthermore, there is a difference in veins and varieties of ores. These differences affect things from both metallurgical and business perspectives[21)]. Viceroy Toledo appointed Velasco (Pedre Hernández de Velasco; birthplace unknown) from Pachuca to conduct experimentation in secret. Based on the results of these experiments, Toledo started implementing his mining policies during his stay at Potosi for general inspections (visita general) from December in 1572 to May in 1573[14)]. Above all, the refinement of desmontes using mercury was promoted. Simultaneously, the mining city plan centered on utilizing hydraulic power was put into practice. Regarding the refinement of desmontes, slag ore was managed by the Royal House, and an order was decreed for these slag ores to be prioritized for refinement during 15 days of each month[44)]. By doing this, underground excavation was cut down and the cost of crushing was decreased, which gave more incentives to Potosi citizens.

Meanwhile, dams, waterways, and crushing facilities using water wheels, etc. were constructed for the introduction of hydraulic power. This idea was almost fully completed during Toledo's leadership. While these series of mining policies were being promoted, the silver yield also steadily increased. In 1581, silver production was six to seven times that of the time Toledo was transferred to Potosi, meaning that he had completed his duty as Viceroy. Figure 1 shows the effects that Viceroy Toledo's various policies had.

After the 5 years post-implementation of Viceroy Toledo's amalgamation method, silver yield through refinement of waste ore was as much as approximately 2 million pesos. This was equivalent to about 30% to 40% of total production yields[15)]. However, there are no records detailing the amount of slag ore consumption, and it is possible that 1/3 to 1/2 of silver went unregistered[12)]. Therefore, the author speculates through calculation that slag ore consumption was approximately 10,000 tons to several tens of thousands of tons[29)]. It also cannot be ignored that the consumption of slag ore caused further organization within and outside of mine shafts. Furthermore, tailings from slag ore generated through the mercury amalgamation method consequently contributed to pulp operation, which will be detailed in the next section.

5.2. Pulp processing and mercury collection

One of the distinctive features of Viceroy Toledo's mining city plan was the arrangement of refinery groups in a cascading style along the waterway and waterway for water wheel power (La Ribera), which ran vertically and horizontally through the city from the group of dams at the water source, as depicted in Figure 5.

Additionally, within the description of the refinery distribution process (Figure 8), the paper indicated that both the pulp (lamas) that was generated by the first stage of ore selection and the pulp generated after washing (relaves) were discarded using the same waterway. The pulp is collected at downstream, at the pozo (a hollow or small pond). There were 50 refineries for mercury collection that used this pulp as raw material, and these refineries collected 2000 quintals of mercury per year[12]. The description also indicates that the composition of the pulp was analyzed and traded based on the analysis[28].

This amount of 2000 quintal was equivalent to approximately 30% of the total mercury used at the Potosi silver mines yearly, which was 7000 quintal (Figure 2)[19]; combined with the amount collected during the amalgam distillation process, approximately 50% of consumed mercury had been re-collected[9]. The use of cascading waterways suggested by Viceroy Toledo was a highly sophisticated technology that holds up to modern standards of efficient energy use.

5.3. Conservation of the fuel plant icho, and thermal efficiency improvements

The natives' Guaira method required high temperatures that necessitated the use of charcoal. However, mercury extraction in the Huancavelica mercury mines and refinement of lamas in Potosi could be conducted under relatively lower temperatures. Therefore, a suitable fuel source was sought after, and icho, also a food for llamas that was grown at plateaus at 4000 meter elevation (dry puna) was found to be ideal. Icho is a rice grass that grows as tall as approximately 60 centimeters, sometimes in 2 years. In Huancavelica, icho was grown in the crop rotation system parallel to development of furnaces with high thermal efficiency. Viceroy Toledo also ordered the conservation of icho[24].

During the same period of time as the silver mining industry in the Viceroyalty of Peru, Mexico (plateau of 2000 meters class elevation) was developing and displaying a different type of phenomena. This phenomenon was major deforestation. Because the German Seiger method of lead refinement was introduced simultaneously with the mercury amalgamation method[20], forests around the mining area were devastated in order to procure charcoal for fuel. This led to a complete change in the surrounding environment[45].

On the other hand, at the Potosi mines, icho was grown by the crop rotation system for mercury refinement and lamas refinement, as described above. It is believed that icho was also used as fuel for building low flames during the cajones method[37].

Peru's mining industry would not have been able to develop without the use of llamas; similarly, it can be said that the refinement of mercury and silver would have been difficult without the use of icho. Ergo, the existence of llamas and icho led Viceroy Toledo's mining policy to success.

Accordingly, when considering the sustainability of the mining industry, local characteristics must be accounted for when making comparative investigations.

5.4. Influences that Viceroy Toledo's various technological policies have had on the modern world (From the perspective of sustainability in the mining industry)

Viceroy Toledo's promotion of waste ore and pulp recycling achieved a great level of success at the time. However, because it was not technically perfect, environmental damage referred to now as mine pollution started from the colonial period and continued until the modern-day period. This pollution can be found in Potosi's air, water, and soil. After reviewing these environmental damages, the following four facts have arisen.

1) The ore from the Potosi mines have always contained a high level of tin and zinc, but only attracted attention in the late 19th century. After silver was exhausted in the Potosi mines, mining still occurred in search of such metals. Before the colonial period, natives lived in houses made of adobe, and because the adobe was made from pulp, the houses were also mined during the period of time when tin was mined. The development t of the Potosi mines can be categorized into the three periods listed below[27].

a) From 1544 to 1884 (340 years); silver period (contained trace amounts of copper)
b) From 1885 to 1985 (approximately 100 years); the golden age of tin (contained Sb, W, Pb, Bi, Cu, Ag and Au)
c) From 1986 to present day; the silver-zinc-copper sulfide period

As can be seen in the vein depicted in Figure 11, there was an enormous silver deposit at the Potosi mines, which is estimated to contain around 7 to 9 hundred million tons of reserved silver[40]. Even now, silver and tin are the main metals produced in the mines, and a notable fact is that the materials in the mines still contain waste ores from the colonial period. The Mankiri Company is currently in charge of refinement of these materials[26].

The current population in Potosi is 170,000 (as of 2013), which surpasses the population during its golden age. Furthermore, Potosi was assigned as a World Heritage by UNESCO in 1987, and has become a tourist city[25].

In order to discuss the proposition of sustainable mine development, it is necessary to examine, through historical details, how the individuals involved in these cases behave.

2) The waterway network in the Potosi mining city connects to the Pilcomayo River (Rio Pilcomayo), outside of Potosi city. The river runs through Argentina to the Atlantic Ocean. Along these waterways, including tributaries, there are mines that were developed after the 16th century which have become sources for water pollution. They have contributed to approximately 500 years of mercury and heavy metal (Pb, Cd, Zn, Cu, etc.) spillage since the mine development in Potosi, and these substances are considered the waterway's main pollutants. In October of 2005, an Environmental Research Project was launched (Projecto Pilicomayo), and investigations are still ongoing[46].

3) Approximately 50% of Potosi's mercury loss is related to the aforementioned river pollution. Simultaneously, mercury has also diffused into the atmosphere to cause soil pollution[47] of areas downwind, and contributed to global air pollution[9][48]. Observations in the South Pole[49] and bottom sediment inspection[50] of local ponds and lakes revealed that this pollution began in the 16th century. Meanwhile, the mercury pollution that started in the Huancavelica mercury mines is also being researched[19]. The most recent task is the discovery of chemically stabilized mercury

in the material of citizens' adobe houses, as well as the soil itself. This accumulated mercury in elements of citizens' daily lives is becoming a mounting concern[51].

4) Mexico's Zacatecas silver mines boasted a capacity as expansive as the Potosi silver mines during the colonial period, and consumed huge amounts of mercury. In the Zacatecas mines, pulp after mercury amalgamation was piled and stored all around the area, and other materials besides mercury such as gold, silver and lead were found[52]. Recently, the business of collecting the silver amalgam from this discarded pulp and waste ore has started to receive attention[53][54]. It is believed that the business of gold and silver collection can be considered useful when taking into account that restoration of mercury-polluted soil can be incorporated into these businesses for other mines that had used mercury refinement.

As discussed above, there are very few accounts of these cases that can be found in historical documents. However, it is apparent that the issues concerning mine pollution started in Spain's colonial period and has continued until now. On the other hand, as apparent from the case of the Potosi silver mines, in a period of time where mining and environmental pollution was not understood as a concept, it is an astonishing fact that the fifth Viceroy Toledo's various policies contained policies and technologies concerning sustainability and recycling, which are requirements in a modern-day recycling-oriented society. Though none of the technology had been perfected, the wisdom and ingenuity of our predecessors are evident. Though we tend to focus on cutting-edge technologies in the current age, there are still things one can learn from the result of archaeological research, as well as from the Cultural Revolution[55] in the middle ages and the ingenuity and new technology developed before the establishment of the chemical equation.

6. In lieu of a summary: The man behind Viceroy Toledo, and his reputation

In the late 16th century, Viceroy Toledo was the one responsible for developing the Potosi silver mines in the Viceroyalty of Peru into a world-acclaimed mining industry. This paper set sustainability as the standard for analysis from the perspective of technical discussion. However, this paper cannot be truly concluded without discussing the Viceroy himself. Thus, this paper refers to past research as reference.

There are not many existing monographs on Viceroy Toledo (Francisco de Toledo y Oropesa). However, besides the 2 pieces of reference that were mainly referred to[56][57], there were frequent mentions of Viceroy Toledo in many historical documents pertaining to Peru during the colonial period. As a summary of important reference segments, in the first half of Viceroy Toledo's post (1569–1572), the Viceroy suppressed a revolt and took great pains in attempting to wipe out the influence of the Incan Empire. After executing Emperor Tupac Amaru on September 24th of 1572, the Viceroy began revitalization of the Potosi mines, and carried out his various policies. As a result, he succeeded in cementing the Spanish monarchy's absolute status in the colonized area. However, the native culture was completely destroyed and exploitation was formalized. This led to a historical grudge being placed upon the Viceroy's period of rule[18)58)].

However, this paper theorizes that the Viceroy was an individual who was successful in establishing big business through systematizing mercury and silver mining through their unification, introducing new technologies, and contributing to the rapid growth of silver production. The following are quotes pulled from 2 to3 historians who have been referred to within this paper, as frank evaluations of the quality of character of Viceroy Toledo.

(1) Exceled as Viceroy of the 40 Viceroys in the Viceroyalty of Peru, but remains an individual who is difficult to evaluate[22)]

(2) Supreme organizational figure in Peru (Suprimo Organizador del Peru)[56)]

(3) The most outstanding figure[57)]

Furthermore, Viceroy Toledo (from the age of 54 to 60) conducted a five-year general inspection (Vista General) that started in 1570. Most of the field work was conducted at the Andes Plateau, a plateau with a 4000 meter-class elevation and 5000 kilometers of travel[22)]. Meanwhile, though he had a myriad of health problems (gout, gall stones, liver disease, etc.)[57)], he completed his duty as Viceroy. This leads one to believe that he was an individual with a strong will. It should be noted that his General Staff Office had a group of advisers that consisted of seven highly capable clergymen, intellectuals (Consejeros), and six executive officers (Eminencias grises)[22)].

According to Zimmermann[57)], this general staff was well acquainted with native society and the general status of the Viceroyalty, and also contributed in making proposals and plans for Toledo. Of them, the following two individuals took notably important roles.

a) Juan Matienzo; Officer at the court of law at La Plata. Excelled in idea-making and planning. Known as the leader (cabezudo) of the group.

b) Polo Ondegardo; Governmental secretary since 1566. Known as an irreplaceable individual.

Besides the above, Jesuit Jose de Acosta (1540–1600), who had experience in the mining industry and the amalgamation method, was also one of the advisers.

The Toledo Family (Count of Oropeza) had an important duty as a member of the chivalric order, and served for Carlos V and Felipe II. As a serviceman[59)] and close adviser to the king, it is believed that Viceroy Toledo was knowledgeable regarding strategic and systematic actions. However, Toledo's return to his country was not strictly triumphant. Suspicion was cast upon him during a work evaluation (Residensia), barring him from even receiving an audience with Felipe II. It is said Toledo's life ended in grief at the age of 67, in 1582[57)].

Contrary to his rise to power and his achievements during his time as Viceroy, Toledo's achievements were not paid off at the end of his life. The last years of Toledo's life is reminiscent to that of Roju Okubo Nagayasu (1545–1613), who worked as a talented mining magistrate and business man in Japan's Edo period[60)61)].

Finally, in this paper, the mining terms used in Latin America during the 16th and 17th century are referred to from the Llanos glossary[62] published in 1609, as well as other references[17][28].

References

1) Japan Oil, Gas and Metals National Corporation. (2005). Global Trends and Undertakings with Respect to the Sustainability of Mining. *Annual Business Report for Intelligence 2005*, No. 3.
2) Otto, J.M., & Cordes, J. (2001). Sustainable Development and the Future of Mineral Investment. Colorado School of Mines, Institute for Global Resources Policy and Management, Metal Mining Agency of Japan. *Collaborative research paper*, No. 35.
3) Akio HATA. (1997). *Technology and Pollution from Metal Production*. AGNE Gijutsu Center.
4) Eiji IZAWA. (2010). Recycling-oriented Society as Seen in Medieval Mining Cities and the Iwami Silver Mines—World Heritage “Iwami Silver Mine Remains and their Cultural Landscape”. *The Resources Processing Society of Japan Academic Lecture* (Kita kyushu city).
5) Shimane Prefecture publicity document. The history of Iwami Ginzan. Shimane Prefecture World Heritage Office.
http://www.pref.shimane.lg.jp/life/bunka/bunkazai/ginzan/outline/#skip
(Reviewed on: December 14th in 2014)
6) Takeo YUASA. (1988). *The Lifeblood of Civilization—World History as Seen through Currency*. Shinhyoron Publishing Inc., pp. 260–322.
7) Eiji IZAWA. (2008). Silver Production from the Middle Ages to the Early Modern Era. *Journal of the Historical Study Group of Mining and Metallurgy*, No. 55, pp. 11–20.
8) Shoji ANEZAKI. (2010). Silver Mining and Mercury Pollution during the Viceroyalty of Peru—Regarding the Mining Business Promoted by the Fifth Viceroy Toledo—, Graduate School of Human Sciences Osaka University, *master thesis*.
9) Shoji ANEZAKI. (2010). Dynamic Regional Studies on Mercury Pollution in Silver Mines in Peru during Spanish Colonization. Graduate School of Human Sciences, Osaka University. *Bulletin for Global Human Study*, **1**, pp. 55–69.
10) Shoji ANEZAKI. (2009). A Technical Study about the Collapse of Caricari Dam of Potosi Mine—Technical Aspects of Mining in Colonial Times of Peru. Graduate School of Human Sciences, Osaka University. *Bulletin for Global Human Study*, **2**, pp. 19–35.
11) Shoji ANEZAKI & Emako MIYOSHI. (2013). Technical Aspects of Mining in Colonial Times of Peru described from the Collapse of Caricari Dam of Potosi Mine. *Proceedings of the Beginning of the Use of Metals and Alloys (BUMA) VIII*, F-11.
12) Acosta, P.J. (1894). Historía Natural y Moral de las Indias. Sevilla: Casa de Fuan de León, pp. 324–346.
13) Probert, A. (1997). Bartollomé de Medina—The Patio Process and the Sixteenth Century Silver

Crisis. In Bakewell P.J. (Ed.), VARIORUM, *An Expanding World-The European Impact on World History 1450–1800*, **19**, pp. 96–129.

14) Bakewell, P.J. (1997). Technical change in Potosi—The silver boom of the 1570's. In Bakewell, P.J. (Ed.), VARIORUM, *An Expanding World-The European Impact on World History 1450–1800*, **19**, pp. 75–95.
15) Bakewell, P.J. (1984). Mining in colonial Spanish America. In Leslie Bethell (Ed.), *The Cambridge History of Latin America, Vol. II, Colonial Latin America*, pp. 105–151.
16) Terry, S. Reynolds. (1989). A History of the Vertical Water Wheel, Translated by Yoshiyuki SUEO, Yoshinobu HOSOKAWA & Yoshiki FUJIWARA. Tokyo: Heibonsha.
17) Arzáns de Orsúa y Vela, Bartolomé. (1965). In Lewis Hanke and Gunner Mendoza (Eds.), *Historia de La Villa Imperial de Potosí, Tomo II*, pp. 1–23. Brown University Press.
18) Tetsuya AMINO. (2008). The Crossing of the Incan and Spanish Empires. *World History of the Rise and Fall 12*, Kodansha.
19) Shuzo MANABE. (2006). The Problem of Mercury Pollution in Huancavelica Mercury Mines during Colonial Peru—The First Half of the Colonial Era—. *Bulletin for Kyoto Institute of Latin-America Studies*, No. 6, pp. 19–55.
20) Yoshiyuki KONDO. (2011). *Silver in Latin America and Capitalism in the Early Modern Era*. Kohrosha.
21) Brading, D.A. & Cross, H.E. (1996). Colonial Silver Mining-Mexico and Peru. In Bakewell, P.J. (Ed.), VARIORUM, *An Expanding World—The European Impact on World History 1450–1800*, **11**, pp. 227–261.
22) Guillermo, L.V. (1986). *Francisco de Toledo—Disposiciones Gubernativas para el Virreinato del Perú, 1569–1574*, pp. 352–354. Sevilla: Escuela de Estudios Hispano-Americanos.
23) Norio YAMAMOTO. (2007). *Andean highlands*, Kyoto University Press.
24) Guillermó, L.V. (1999). *Las Minas de Huancavelica en los siglos X VI yX VII*, pp 136–142. Lima: PONTIFICIA UNIVERCIDAD CATORICO del PERÚ.
25) Ríos, L.P., Soro, F.P. (Selec.) & Potosí (Honorable Gobierno Municipal de Potosí)/Madrid (Agencia Española de Cooperación Internacional)/Sevilla (Junta de Andalucía—Consejería de Obras Públicas y Transportes—Dirección General de Arquitectura y Vivienda), (Ed.) Potosí, Bolivia Junta de Andalucía—Consejería de Obras Pública y Transporte/Honorable Gobierno Municipal de Potosí. (2004). *Potosí Guía de Arquitecutura*, pp. 16–51.
26) Potosí de Wikipedia. (2013). la Enciclopedia libre.
27) Carlos Serrano Bravo. (2009). Ejemplos de Contaminación Sostenida. *Segundo Congreso Internacional sobre Geología y Minería en la Ordenación del Territorio y en el Desarrollo*, pp. 25–41.
28) Capoche, L. (1959). In Hanke, L. (Ed.), *Relación general de Villa Imperial de Potoí*, pp. 69–111. Madrid.
29) Shoji ANEZAKI, Takaiku YAMAMOTO & Emako MIYOSHI. (2014). Recovery of Silver from

Tailings and Mercury in Abandoned and Contaminated Soils at the Potosi Mine under the Reign of Fifth Viceroy Toledo during Spanish Colonial Rule—An Environmental Study based on the Historical Documents. *Journal of Japan Society of Material Cycles and Waste Management*, **25**, 6, pp. 445–453.

30) Cole, A.J. (1985). *The Potosí Mita 1573–1700*, p. 7. California: Stanford University Press.

31) Bakewell, P. (1989). *Mineros de la Montaña Roja-el trabajo de los indios en Potosí 1545–1650*. Versión española de Mario García Aldonato, Alianza Editorial.

32) Alvaro Alfonso Barba. (2003). *Arte de los Metales (Ed. 1639)*, Editional MAXTOR.

33) Shuzo MANABE. (2012). Socio-economic Research Concerning Silver Mines—The Creation of the Potosi Market Economic Area (Part 1). *Bulletin for Kyoto Institute of Latin-American Studies*, **11**, pp. 57–84.

34) Shuzo MANABE: Socio-economic Research Concerning Silver Mines—The Creation of the Potosi Market Economic Area (Part 2), *Bulletin for Kyoto Institute of Latin-American Studies*, vol. 12 (2013), pp. 1–31. Tokyo: Kokon Syoin.

35) Jose de Acosta. (1966). *Natural Cultural History of the New World (Part 2)*, Translated by Yoshiro MASUDA. Iwanami Shoten.

36) Percy, J. (1880). *Metallurgy-Silver and Gold 1*, pp. 649–666. London: John Murray.

37) Bargalló, M. (1955). *La Minería y la Metallúrgia en la América Español durante la época colonial*, pp. 107–195. Mexico: Fondo de Cultura Economía.

38) Cieza de Leon. (2007). *Inca Empire topography*, pp. 545–558. Translated by Yoshiro MASUDA, Iwanami Bunko.

39) C.G. Cunningham, R.E. Zartman, E.H. Mackee et al. (1996). The age and thermal history of Cerro Rico de Potosi, Bolivia. *Mineral Deposita*, **31**, pp. 374–385.

40) Tadashi MARIKO. (2008). *Mineral Deposit Geology—Study of Mineral Deposits of Metal Resources*, pp. 226–231.

41) Fumio KISHIMOTO. (1979). *The Creation of Metal Resource Deposits—Wide-scale Distribution Law of Deposits—*. Gendai Kogyosha.

42) Mario, R. De Nigris & Octavio Puche Riart. (2011). El Uso de Hornos y Guaira para la Fundación en los Andes. *De Re Metallica*, **16**, pp. 21–31.

43) Shuji FUNO and Juan Ramon Jimenez Verdejo. (2013). *The Grid City-The Origin, Formation, & Transformation of Spanish Colonial Cities*, pp. 388–397 and frontispiece 6. Kyoto University Press.

44) Guillermo, L.V. (1989). *Francisco de Toledo—Disposiciones Gubernativas para el Virreinato del Perú, 1575–1580*, pp. 299–300. Sevilla: Escuela de Estudios Hispano-Americanos.

45) Daviken Studnicki-Gizbert & David Schecter. (2010). The Environmental Dynamics of a Colonial Fuel Rush—Silver Mining and Deforestation in New Spain 1522–1810. *Environmental History*, **15**, pp. 94–119.

46) Project Pilcomayo. Selected Results, (2005).

http://paws.wcu.edu/jmiller/Results_Pilcomayo.html
(Reviewed on: August 18th in 2009)

47) Susumu OGAWA, Naoki OKADA & Ryosuke SHIBASAKI. (2008). The Estimation of Mercury Pollution due to Development of the Potosi Silver Mines in South America. *Autumn Lecture of The Society of Photography and Imaging of Japan*, K-6, pp. 155–158.
48) Hylander, L.D. (2003). 500 years of mercury pollution—global annual inventory by region until 2000 and associated emissions. *The Science of the Total Environment*, No. 304, pp. 13–27.
49) Yuriko YOSHIDA & Masayo MUROZUMI. (1977). Mercury profile of Mizuho ice sheet in Antarctica. *Antarctic Record*, **59**, pp. 26–29.
50) Cooke, C.A., Balcom P.H. & Biester H. et al. (2009). Over three millennia of mercury pollution in the Peruvian Andes. *PNAS*, **106**, pp. 8830–8834.
51) Nicholas, A. Robins. (2011). *Mercury, Mining, and Empire*, pp. 1–12. Indiana University Press.
52) MC/4030-01-02 Project. (2008). *Sequential Chemical Specification of Mercury in Contaminated Sites of Mexico*. UNEP & UNUM, Coordinated by Elvira Santos-Santos y Irma Cruz-Gavilan.
53) Ogura, T., Ramirez-Ortis J. & Martinéz, S.H. et al. (2003). Zacatecas (Mexico) Companies Extraction Hg from surface soil contaminated by ancient mining industries. *Water, Air, and Soil Pollution*, **148**, pp. 167–177.
54) Raminez Álvarez J. A. y Eden Wynter R. A. (2000). *Status of Mercury in Mexico*, First Draft.
55) Yoshitaka YAMAMOTO. (2007). *Cultural Revolution in the 16th Century*. Misuzu Shobo.
56) Roberto Levillier. (1935). *Don Francisco de Toledo-Suprimo Organizador del Peru-Su Vida, su Obra (1515–1582)*, Buenos Aires: Biblioteca del Congreso Argentino.
57) Franklin Zimmermann. (1968). *Francisco de Toledo-Fifth Viceroy of Peru (1569–1582)*, New York: Greenwood Press.
58) Hidefuji SOMEDA & Hiroyasu TOMOEDA. (1992). *The "Truth" as Written by the Andes Chronicler Guaman Poma*, Heibonsha.
59) Kentaro UENO. (2000). *The Journey of Carlos the Fifth*, Japan Travel Bureau.
60) Takashi KAWAKAMI. (2012). *The Mystery of Okubo Nagayasu—Gold Mining Magistrate in the Edo Period*, Gendai Shokan.
61) Tadashi MURAKAMI. (2013). *Researches about Okubo Nagayasu, the Head of Magistrate*, Youransha.
62) Garcia de Llanos. (1983). In Ramiro Molina Barrios (Ed.), *Diccionario y Maneras de Hablar que se usan en las Minas y sus Labores en los Ingenios y Beneficios de los Metales (1609)*, La Paz Bolivia: Museo Nacional de Etnografía y Folklore.