



Boletín del Museo Chileno de Arte  
Precolombino

ISSN: 0716-1530

atorres@museoprecolombino.cl

Museo Chileno de Arte Precolombino  
Chile

Van Buren, Mary; Cohen, Claire R.  
TECHNOLOGICAL CHANGES IN SILVER PRODUCTION AFTER THE SPANISH CONQUEST IN  
PORCO, BOLIVIA

Boletín del Museo Chileno de Arte Precolombino, vol. 15, núm. 2, 2010, pp. 29-46

Museo Chileno de Arte Precolombino  
Santiago, Chile

Available in: <http://www.redalyc.org/articulo.oa?id=359933363003>

- How to cite
- Complete issue
- More information about this article
- Journal's homepage in redalyc.org

redalyc.org

Scientific Information System  
Network of Scientific Journals from Latin America, the Caribbean, Spain and Portugal  
Non-profit academic project, developed under the open access initiative

# TECHNOLOGICAL CHANGES IN SILVER PRODUCTION AFTER THE SPANISH CONQUEST IN PORCO, BOLIVIA

## CAMBIOS TECNOLÓGICOS EN LA PRODUCCIÓN DE PLATA DESPUÉS DE LA CONQUISTA ESPAÑOLA EN PORCO, BOLIVIA

MARY VAN BUREN\* & CLAIRE R. COHEN\*\*

### INTRODUCTION

Over the last decade, the Proyecto Arqueológico Porco-Potosí has investigated the Bolivian mining center of Porco in order to examine silver production under the Inka, Spanish, and Republican regimes. One focus of this research is the ways in which metallurgy was shaped by Porco's incorporation into the colonial world. After 1572, mercury amalgamation was the dominant method for refining silver ores, but at Porco, smelting technologies continued in use and were particularly varied. This paper represents a first step towards understanding this variability. It examines two technologies, native huayrachinas and European reverberatory furnaces, in order to determine how they functioned and were modified over time. We address this issue by describing their disposition within the archaeological record, assessing their use through slag analysis, and finally examining their historical development.

**Key words:** metallurgy, smelting, silver, mining, Colonial Period, Andes, Bolivia

*Durante la última década, el Proyecto Arqueológico Porco-Potosí ha investigado el centro minero boliviano de Porco para examinar la producción de plata bajo los gobiernos de los Inka, los españoles y la República. Un enfoque de estos estudios ha examinado las maneras en que la metalurgia fue cambiando cuando Porco se incorporó al mundo colonial. Aunque desde 1572 la amalgamación del mercurio fue el método predominante para refinar el mineral de plata, en Porco las tecnologías de fundición continuaban en uso, con bastantes variaciones. Este artículo representa un primer paso para entender esta variabilidad. Se examinan dos tecnologías, las huayrachinas nativas, y los hornos de reverbero europeos, para determinar cómo funcionaban y cómo fueron modificados en el tiempo. Abordamos este tema con una descripción de su disposición dentro del registro arqueológico, evaluando su uso a través del análisis de escorias, y, finalmente, examinando su desarrollo histórico.*

**Palabras clave:** metalurgia, fundición, plata, minería, período colonial, Andes, Bolivia

Potosí is renowned for being the site of the largest silver deposit in South America and the economic engine of the Andean economy in the early Colonial Period. However, the smaller nearby center of Porco had been worked by the Inka and was one of the first silver mines exploited by the Spaniards in the Andes (fig. 1).<sup>1</sup> Its distance from large population centers and decline after the discovery of Potosí in 1545 also resulted in relatively good preservation of the archaeological record. For these reasons, it was selected for study by the Proyecto Arqueológico Porco-Potosí, a multidisciplinary research program that has as its overarching goal the research of the organization of silver production under the Inka, Spanish, and Republican regimes. One key focus of this investigation is the ways in which metallurgical technology was shaped by Porco's incorporation into the Spanish colonial world. Historians have produced a substantial body of research on silver production in Potosí during the first few decades after its discovery and especially on the social and technological changes that occurred in the wake of the reforms implemented by Viceroy Toledo in 1572 (e. g. Bakewell 1984a; Cole 1985; Assadourian 1992; Serrano & Peláez 1992; Craig 1993, 1994; Tandeter 1993; Castillo Martos 1994; Serrano 1994; Castillo Martos & Lang 1995; Salazar-Soler 1997b, 2002; Garavaglia 2000;

\* Mary Van Buren, Department of Anthropology, Colorado State University, Fort Collins, CO 80523, USA, email: mary.vanburen@colostate.edu

\*\* Claire R. Cohen, University College London, 3 Orchid Court, 171 Granville Road, London NW2 2BE, UK, email: nehoccc@gmail.com



Figure 1. Map of Bolivia showing location of Porco.

Figura 1. Mapa de Bolivia indicando la ubicación geográfica de Porco.

Mira 2000). With few exceptions (Rodríguez Ostria 1989; Tandeter 1993) these investigations have focused on the adoption of mercury amalgamation, a refining technique that required the construction of large stamp mills and a substantial labor force, much of it supplied by the newly instituted *mit'a*. The large amounts of capital needed to construct mills and purchase mercury resulted in a shift from native to Spanish control of the productive process, and mine and mill owners of European descent dominated the industry throughout colonial times as a result. However, native production using small-scale technology has also continued into the present, and at some points in history generated a substantial portion of the silver produced in the region (Rodríguez Ostria 1989; Tandeter 1993: 92-93).

A decade of excavation and survey in Porco has revealed that rather than being completely replaced by mercury amalgamation, smelting technologies continued in use and were particularly varied during the first half of the Colonial Period (1538 to approximately 1675). *Huayrachinas* (native wind furnaces) co-existed with a variety of open hearths, as well as reverberatory furnaces, no two of which are identical. As has been clearly demonstrated by archaeologists over the last two decades, the factors shaping an individual technology are themselves varied (Killick 2004) and include the availability of raw materials, the cost and efficiency of a specific process, its historical origins, and the nature of the society in which it is used, among other variables.

In this paper we attempt to unravel some of these factors in a first step towards understanding the history

of small-scale silver production over the long-term. We focus on two smelting and refining technologies that were common in Porco during the Colonial Period: *huayrachinas* and reverberatory furnaces. The co-existence of these two types of furnace raises the question of how they were related. Were they combined and used sequentially in the same chain of production? Or were they employed by different people for fundamentally the same purpose? Did they remain static, or change over time, and if so, why? We address these questions in three steps. First, the historical antecedents of these furnaces and their disposition within the archaeological record at Porco are described. Second, the ways in which these furnaces were used are assessed through the analysis of associated slags. The more complex problem of how smelting and refining technology changed over time is then briefly addressed by examining these furnaces in a broader temporal and geographic context. The results of this analysis suggest that native workers creatively fused indigenous and European technologies in order to undertake new socio-economic challenges.

## A BRIEF HISTORY OF MINERAL PRODUCTION IN PORCO

Porco is located in southern Bolivia, 35 km southwest of Potosí, and is currently the largest producer of zinc in the country. According to colonial sources, it was an important Inka mine, supplying the silver that was used to adorn the Korikancha in Cuzco (Cieza de León 1984: 372) and the royal litter (Ocaña 1969: 182). Historians have suggested that prior to the arrival of the Inka the mines were worked and venerated by members of the Charka confederation, a loose alliance of *señoríos* that occupied southern Bolivia at the time of the Spanish conquest (Platt 2000; Platt et al. 2006). Survey and excavations conducted over the last decade, however, have not revealed any evidence of pre-Inka use. Thus far the archaeological record indicates that the silver deposits at Porco were first exploited by the Inka who employed *mit'a* laborers to extract the ore, and *yanakuna*—specialists who were attached to elites—to smelt and refine it (Van Buren & Presta 2010). The mines were claimed by Gonzalo and Hernando Pizarro immediately after the Spanish conquest (Presta 2008), and silver continued to be extracted and processed by indigenous laborers, both *encomienda* Indians and *yanaconas*, retainers who may have worked previously under the Inka and who became attached to individual Spanish mine owners during this period. Porco was rapidly eclipsed in importance after the discovery of

silver in Cerro Rico in 1545, but in both centers silver continued to be extracted and processed largely by native people employing indigenous technology, most notably *buayrachinas* (Bakewell 1984a: 14-17).

Indigenous control over production largely came to an end in 1572 when mercury amalgamation was introduced by Viceroy Toledo as part of a package of reforms intended to reinvigorate the mining sector and augment revenues for the Crown. The refining of large quantities of lower grade ores through amalgamation required the construction of expensive stamp mills which were beyond the financial means of indigenous workers. Stamp mills, owned and operated by Spaniards, dominated the industry in Potosí (Bakewell 1997), where they were powered by water descending from reservoirs constructed in the Kari-Kari range to the east of the city (Serrano & Peláez 1992). The stream closest to Porco, Río Yana Machi, though, does not carry enough water to power a wheel, and no evidence for stamp mills has been recovered in the immediate vicinity of the mines. However Luis Capoché, a sixteenth century observer, noted that mills had been constructed on the nearby Agua de Castilla and San Juan Rivers by 1585 (Capoché 1959: 125), and the latter mill may underlie an eighteenth century complex, Ferro Ingenio, that was identified 7 km to the southeast of Porco during a survey of that section of the river (Weaver 2008).

Smelting continued to be important in Porco, as indicated by Alonso Barba (1992 [1640]: 141) a priest and miner from Potosí who had first-hand knowledge of the region, as well as by the abundant evidence for colonial furnaces in the archaeological record. The two most commonly encountered furnace types are *buayrachinas* and reverberatories, whose historic origins lie in the Andes and Europe, respectively.

## HUAYRACHINAS AND TOCOCHIMBOS

*Huayrachinas* are an indigenous technology employed by the Inka to smelt silver and copper (Zori & Tropper this issue), and they continued to be used after the Spanish conquest. In fact, almost all of the silver produced in Potosí from its founding in 1545 until the introduction of mercury amalgamation in 1572 was smelted in *buayrachinas* operated by *yanaconas* (Bakewell 1984a: 49-50). A number of early chroniclers provide evidence for the use of *buayrachinas* and associated refining technologies (Acosta 1954; Capoché 1959; Ramírez 1965; Cieza de León 1984; for a later description see Alonso Barba 1992 [1640]; see Oehm 1984 and Van Buren & Mills 2005 for summaries). Although there is some variation

in the colonial descriptions, these furnaces were usually constructed of clay or stone, were cylindrical in cross-section, and reached approximately one meter in height. The top of the furnace was open, and the sides were perforated by holes that allowed the wind to oxygenate the charge, which consisted of charcoal mixed with ore and litharge. They were erected on hills and ridge tops and often operated at night to take advantage of the strong winds that begin just prior to sunset.

Historical sources indicate that the lead-silver bullion produced in *buayrachinas* was next refined in *tocochimbos*.<sup>2</sup> These are poorly described in the colonial literature most likely because they were not easily observed by outsiders. Early colonial writers indicate only that they were located in native homes and were small and round, had a gentle flame, and were used with a blowpipe or bellows (Van Buren & Mills 2005). As bellows were not known in the Andes in pre-Hispanic times, the latter observation reflects the rapid adoption of a European technology with a functional equivalent in the Andean repertoire. The only known image of a *tocochimbo* was published in 1640 by Alonso Barba (1992 [1640]: 141). He depicts it as a round muffle furnace and indicates that while it had previously been used only for refining, at the time of writing it was sometimes employed to smelt small quantities of high grade silver and gold ore. Muffle furnaces have not been identified at pre-Hispanic Andean sites, but they were commonly used in sixteenth century Europe to assay and refine silver (Agricola 1950 [1556]: 489-490; Biringuccio 1990 [1540]: 139-140). Alonso Barba's illustration was published a century after the Spanish conquest and probably represents a technology that was introduced by Europeans, rather than a pre-Hispanic practice. We thus know that very early in the Colonial Period, and probably in the Late Horizon as well, indigenous silver production in the Potosí region was a two-stage process involving first smelting in a *buayrachina* and then refining (Oehm 1984); but the type of furnace used in this second step and the way in which it functioned is still unclear. Four formal, open hearths were uncovered in late sixteenth and early seventeenth century archaeological contexts at Porco, and may, in fact, be *tocochimbos* (fig. 2). All were found within structures, were heavily burned, and were associated with small quantities of metallurgical debris. However, as analysis of this debris has not yet been conducted, their precise function is unknown.

The remains of *buayrachinas* occur in abundance on the ridges immediately surrounding the present-day village of Porco (fig. 3). While the continual re-use of these sites precludes precise dating of individual furnaces, Late Horizon and colonial ceramics are commonly





Figure 2. Possible tocochimbo located during excavation of an early colonial structure near the site of HuA1 (see map).

*Figura 2. Posible tocochimbo hallado durante la excavación de una estructura colonial temprana, cerca del sitio HuA1 (ver mapa).*



Figure 3. Huayrachina remains at Porco.

*Figura 3. Restos de una huayrachina en Porco.*

intermixed with *buayrachina* fragments found there. Another pattern characterizes smelting remains at a distance from the mines, most of which either contain nineteenth or twentieth century artifacts or lack diagnostic material. Small quantities of *buayrachina* fragments are located on ridges above isolated homesteads, and the remains of cupellation hearths are found nearby in *quebradas* or against rock outcrops. These cupellation hearths are, in fact, diminutive reverberatory furnaces that consist of a small, round hearth at the center with a chimney on one end and a fire box on the opposite side. Observations of current metallurgical practice indicate that they were used to purify the lead-silver bullion produced in *buayrachinas* (see below), so we refer to them here as “cupellation hearths” in order to distinguish them from the larger reverberatory furnaces that were introduced by the Spaniards.

Small-scale silver production that incorporates some aspects of ancient practice is still conducted near Porco and provides insight into the archaeological record. It is currently part of a diversified household economy that includes agriculture and wage labor. Pockets of high grade ore are occasionally encountered in the mines and “stolen” by miners who sometimes have it smelted prior to selling it in Potosí. Traditional smelters continue to employ *buayrachinas* to produce lead (fig. 4), which is then used to refine silver ore in a small cupellation furnace of the type described above. Today these furnaces are constructed within an adobe hut close to the smelter's estancia (fig. 5). The furnace is constructed of stone and lined with clay, and spans the width of the structure. It has a round opening on the top and apertures on both sides; all but one of these are luted in place before firing. Llama dung is used for fuel and is continuously added and stirred for the duration of the process. The hearth, which is approximately 30 cm in diameter, is lined with yareta ash that is tamped down to form a slightly concave floor. Lead metal produced by the *buayrachina* is placed in the hearth and heated until it forms a lead bath. Finely ground silver ore is then introduced through a side opening and slag is removed with a rabble. This process continues until all the lead either soaks into the ash floor or evaporates, leaving a button of pure silver on the floor of the hearth (Van Buren 2003; Van Buren & Mills 2005).

Whether the cupellation hearth that is used today is a *tocochimbo*—or a different technology that serves the same purpose—is not entirely clear. The use of cupellation by Andean metallurgists in pre-Hispanic times has been inferred by a number of archaeometallurgists on the basis of silver objects that contain small percentages of lead (Howe & Peterson 1994; Gordon & Knopf 2007), or from

waste associated with scorification, an intermediate stage between smelting and cupellation (Schultze et al. 2009). However, no direct evidence for pre-Hispanic cupellation hearths has been identified in the archaeological record to date, so the way they were constructed is unknown. We argue that the morphological similarities between the cupellation hearths used in Porco and colonial reverberatories identified in the archaeological record and described in metallurgical treatises (Agricola 1950 [1556]: 483; Alonso Barba 1992 [1640]: 136-138) suggest that they are modified versions of European furnaces, an issue that is discussed below.

## LARGE REVERBERATORY FURNACES

Reverberatory furnaces are configured so that the mineral being processed does not come into direct contact with the fuel. This is most often accomplished by constructing a firebox adjacent to the hearth but separated from it by a partition. The hot air flows over the partition and into the reaction chamber where it is reflected downward from the domed roof and concentrated on the hearth. The early history of reverberatory furnaces in Europe has not been fully explored, but they are described by both Vannoccio Biringuccio (1990 [1540]) and Georgius Agricola (1950 [1556]) in their classic sixteenth century treatises on mining and metal production. Biringuccio discusses the use of reverberatories in two contexts. First, he briefly describes hearing about the use of such a furnace for smelting ores, a practice that he had not witnessed and which he does not endorse, preferring, instead, a blast furnace for that purpose (Biringuccio 1990 [1540]: 150-152). Second, he describes the employment of reverberatories for melting bronze and provides clear plan views that indicate how they are configured (fig. 6); a firebox with a grated floor is shown adjacent to, but separated from the hearth (Biringuccio 1990 [1540]: 281-288). In contrast, Agricola (1950 [1556]: 483) associates the use of reverberatory furnaces with cupellation. The clearest parallel with the reverberatories in Porco that he describes are the furnaces used by Hungarians and Poles to separate lead from silver. These were domed and had a grated firebox on which wood was burned adjacent to the reaction chamber. The fire was oxygenated with bellows, and the litharge flowed out an aperture on the side opposite the firebox.

While Central Europe may seem distant from the Spanish colonial world, a strong case can be made that the transfer of reverberatory technology from this region to the Americas was the result of the Spanish Crown's relation to the Fugger banking company. The





Figure 4. Modern huayrachina used by Carlos Cuiza to produce lead metal.

*Figura 4. Huayrachina moderna utilizada por Carlos Cuiza para producir plomo metálico.*





Figure 5. Modern cupellation hearth used by Carlos Cuiza to refine silver. The opening to the fire box can be seen to the right; the door to the hearth itself is on the left.

*Figura 5. Horno de copelación moderno utilizado por Carlos Cuiza para refinar plata. La apertura a la caja de fuego puede verse a la derecha; la puerta del fogón mismo está a la izquierda.*

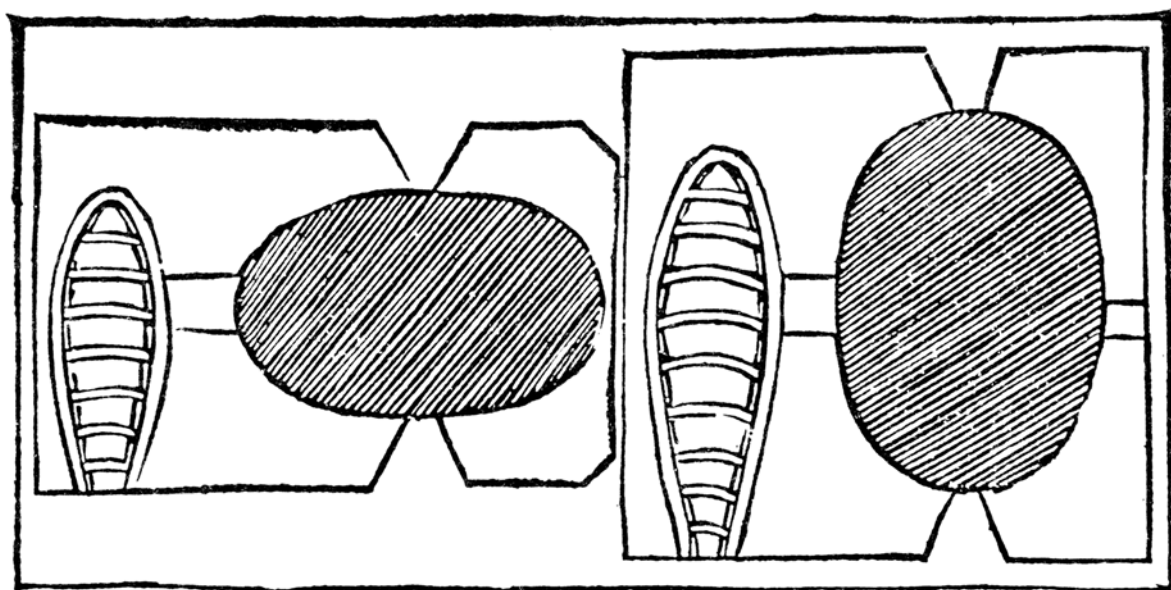


Figure 6. Plans of two reverberatory furnaces with oval hearths illustrated by Biringuccio (1990 [1540]: fig. 40). Fireboxes with grated floors are depicted at left of hearths and connected to them by fire bridges.

*Figura 6. Planos de dos hornos de reverbero con fogones ovalados, dibujados por Biringuccio (1990 [1540]: fig. 40). Al lado izquierdo de los fogones se encuentran las cajas de fuego con pisos rejillas, conectados a través de puentes de fuego.*



Fuggers were an extraordinarily wealthy family from southern Germany, and in the late fifteenth and early sixteenth centuries controlled an extensive network of argentiferous copper mines and large plants for metal production in Germany, Hungary, southern Austria and what is now Poland, among other places (Neff 1941; Graulau 2008). Unlike the spice trade, in which the House of Fugger also participated, investment in mining and metallurgy required involvement in the productive process. Access to technical expertise was facilitated by the business partnerships and marriages that were arranged between the Fuggers and the Thurzos, a family of mining entrepreneurs and engineers from Cracow (Graulau 2008).

The Fuggers were also among the largest lenders to the Hapsburg kings, and the financial fortunes of the Fugger banking company and the Spanish Crown were intimately tied. In 1528 Carlos I requested that the Fuggers provide experts for improving mining and metallurgy in the Americas. German miners were sent to the Caribbean and Venezuela, and many ended up in what is now Mexico. There they introduced the use of a Castilian blast furnace to smelt silver ores, followed by cupellation in a reverberatory furnace (Bakewell 1984b). This procedure was employed in the decades following the Conquest of Mexico; Gómez de Cervantes (1944 [1599]: 158-161) describes it as a process that had already been superseded by amalgamation throughout Nueva España.

Reverberatory furnaces—which have not been identified in pre-Hispanic contexts in the Andes—thus have clear antecedents in Europe where they were employed for a variety of purposes, with refining and melting being their primary functions. While precisely how this technology was introduced to the Andes remains to be discovered, the use of cutting-edge techniques for producing silver was promoted by the Spanish Crown and its financial backers, and then probably adopted by metallurgists who learned it from one another.<sup>3</sup>

Alonso Barba (1923 [1640]: 222) describes reverberatory furnaces in great detail, and discusses their use for roasting, refining, and smelting ores. In contrast to the European writers, he emphasizes the latter process and, in fact, notes that a historical change had occurred in the use of this technology:

Up to these our present times, the smelting of ores in reverberatories has been little used, or not at all, by those treating ores; and, although reverberatories were known in the past, they were not of the perfected types used today, nor were they used for smelting, but for refining only. A sufficient proof of this is that Georg Agricola, who wrote so extensively on everything pertaining to metallurgy, does not mention their use for smelting.

Alonso Barba (1992 [1640]: 136-138; 142-143) provides instructions for making two types of reverberatory furnaces for smelting ore which, when constructed on a smaller scale and lined with ash, could also be used for refining silver, or cupellation. Both types consist of square platforms in which circular hearths are constructed and lined with carbonilla, which is a mixture of earth and charcoal. A domed roof with a circular opening large enough for a person to enter is placed on top of this. To one side of the hearth is a rectangular firebox provided with a grate on which wood is burned to fire the furnace. The first type of furnace has either a narrow opening or rectangular chimney on the opposite side of the hearth that allows the smoke to escape. Triangular windows are left on the two remaining sides for the use of a bellows, if needed, and so that metal can be added and stirred, or slag can be removed. The second type is distinguished only by the form of the chimney, which is large and inclined, rather than vertical. Alonso Barba (1992 [1640]: 142-143) reports that this type of reverberatory is called a “dragon” on account of its shape and the amount of mineral that it could consume, and states that it was used primarily to smelt lead (fig. 7).

Both types of large reverberatory furnace described by Alonso Barba are found in the archaeological record at Porco, although they are no longer used. Pedestrian survey revealed that, with two exceptions, they are located close to mines in areas that are clearly industrial, and most date to the Colonial Period. The first exception is a relatively small furnace that was constructed within a *quebrada* adjacent to Dionicio Eco's rural homestead which is approximately 4 km to the northwest of Porco. *Huayrachina* fragments were encountered on a nearby ridge. The furnace's location and association with charred camelid dung are similar to the cupellation hearths used today. However, it is larger than such furnaces, does not have a chimney, and was not enclosed within a building. Taken together, these characteristics suggest that it may be a smaller version of a domed reverberatory, perhaps an antecedent to the type of cupellation hearth that is used in conjunction with *huayrachinas* today. The second exception is a “dragon” furnace located on an estancia approximately 8 km to the west of Porco; it is described in more detail in the following section.

## THE ANALYSIS OF HUAYRACHINA AND REVERBERATORY FURNACE SLAGS

The archaeological record of colonial smelting at Porco includes a diverse set of facilities used in the production of silver, but the way in which these were related

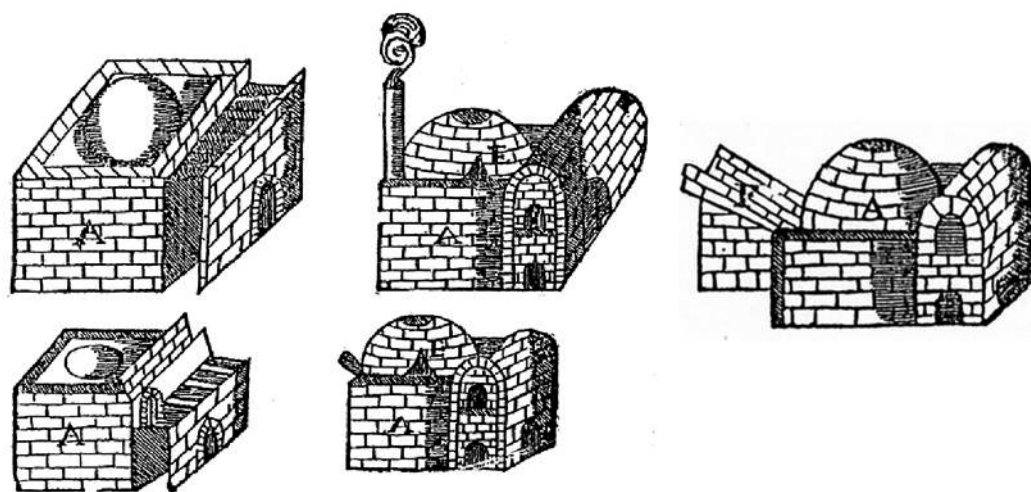


Figure 7. Drawing of two styles of reverberatory furnace by Alonso Barba (1992 [1640]: 138,143). "Dragon" furnace is on the right.  
 Figura 7. Dibujos de dos estilos de horno de reverbero, realizados por Alonso Barba (1992 [1640]: 138,143). A la derecha está representado el horno estilo "dragón".

—functionally and historically—is difficult to determine. Since European reverberatory furnaces appear to have been employed primarily for refining, their occurrence at the same time as *huayrachinas* suggested the possibility that the two were used in tandem to first smelt and then refine silver ore. As a first step towards unraveling this problem, the functions of these furnaces were assessed by analyzing associated slags.

Samples of slag produced by *huayrachinas* were selected from five sites that are located on ridges to the north of Cerro Huayna Porco (fig. 8). Two of these, HuA1 and Hu24 are dated to the early and middle Colonial Period on the basis of associated ceramics. However, both also yielded provincial Inka sherds, a ceramic type that was produced during the Late Horizon as well as the early Colonial Period. Three other sites (Uruquilla West, Uruquilla East, and Cruz Pampa) are not associated with diagnostic artifacts and remain undated; they are located, however, on ridges to the east and west of the site of Uruquilla and immediately above the domed reverberatory furnaces described below.

*Huayrachinas* rarely remain intact for more than a few years since they are typically constructed on ridge tops and hills that are subjected to high winds and erosion (Van Buren & Mills 2005). They do, however, leave a distinctive signature in the archaeological record. These sites consist of thick furnace fragments that are sometimes perforated and often vitrified on the interior surface, mixed with fire-reddened rocks, small pieces of charcoal, and slag. *Huayrachina* slag, unlike that produced by the reverberatory furnaces described above, is

usually somewhat spongy in appearance and lacks the ripples that are typical of slag that has reached a high enough temperature to melt completely. In addition to these artifacts, sites where *huayrachinas* have been used often include flat rocks on which the furnaces were constructed as well as low stone walls that were used as wind breaks. These features characterize the sites on the ridges surrounding the modern village of Porco, including those adjacent to Uruquilla.

Twenty-four slag specimens collected from HuA1, Hu24, Uruquilla West, Uruquilla East, and Cruz Pampa were analyzed in the Wolfson Laboratory at the Institute of Archaeology at University College London using optical microscopy, SEM-EDS, and XRF (Cohen 2008). These analyses indicate that the slags are lead silicates that commonly contain metallic prills composed of lead or silver-rich lead metal and areas of lead sulphide (fig. 9). However, slag composition is highly variable (Table 1). Quantities of lead oxide range from 8 to 66wt%; lime and alumina were contributed by the interaction of the lead oxide with the ceramic body of the furnace. Heavy metals such as iron and zinc oxides are almost always present and range from a few percent to 17%. Some samples lie outside the norm; one slag from Uruquilla East, for example, contains up to 13% tin oxide, and a sample from HuA1 contains higher than expected magnesium oxide (8%), with relatively low lime and some antimony. Such variation indicates that the ore being processed was obtained from different veins.

The presence of lead sulphide as well as metallic lead and silver indicate that the ore was an unroasted



Figure 8. Map of the area surrounding Porco showing the location of Cerro Huayna Porco, as well as the sites of Uruquilla, Cruz Pampa, HuA1 and Hu24, which are mentioned in the text. Uruquilla East and West are small hills on either side of Uruquilla. Small squares on the map represent reverberatory furnaces, and triangles indicate cupellation hearths. The map was produced by Brendan Weaver on the basis of a Google Earth image.

*Figura 8. Mapa de los alrededores de Porco, indicando la ubicación del Cerro Huayna Porco y los sitios de Uruquilla, Cruz Pampa, HuA1 y Hu24 mencionados en el texto. Uruquilla Este y Oeste son dos pequeños cerros ubicados en cada lado de Uruquilla. Los cuadrados pequeños en el mapa representan hornos de reverbero y los triángulos indican hornos de copelación. El mapa fue realizado por Brendan Weaver sobre la base de una imagen de Google Earth.*

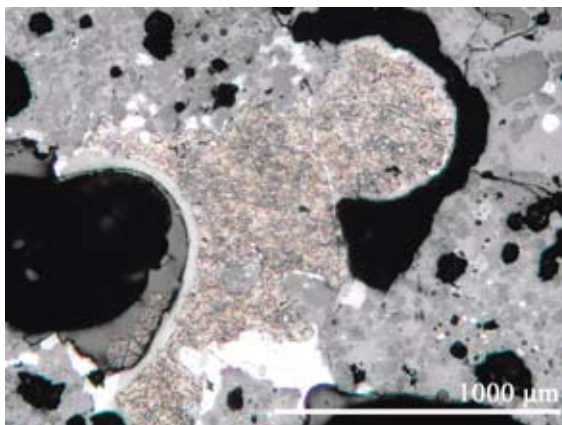


Figure 9. OM photograph of slag associated with huayrachinas at site HuA1. Note metallic lead at center (brown) with areas of lead sulphide (bright white) along outer rim.

*Figura 9. Fotografía MO de escoria asociada con huayrachinas en el sitio HuA1. Al centro, bay plomo metálico (café) con áreas de sulfuro de plomo (blanco intenso) en el borde exterior.*

argentiferous galena. The slag analysis shows that furnaces operated under high temperatures and relatively oxidising conditions. These redox conditions created a lead silicate slag with different silicate phases and inclusions of silver-lead metallic prills. A silver-rich lead bullion would have been produced that would have needed further refining.

Slag samples associated with three reverberatories at Uruquilla and a fourth “dragon” furnace from a nearby estancia were also analyzed. Uruquilla, also known as “Porco Viejo,” is located just above and to the south of the contemporary village. It consists of agglutinated rectangular structures arranged in irregular rows that are separated from a plaza to the south by two large rock outcrops. The entire settlement is enclosed by a stone wall to the east, south, and west; to the north the site is delimited by a steep quebrada with a perennial stream.



Table 1. SEM-EDS bulk area analyses of slag samples from sites in Porco.\*  
 Tabla 1. Análisis agregado MEB-EDS de muestras de escoria tomadas de varios sitios de Porco.

Bulk Composition	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	MnO	FeO	ZnO	As2O5	Sb2O3	SnO2	PbO
Hu24 77C	–	3.5	5.9	32.8	1.2	0.9	2.4	23.5	0.2	–	10.3	11.6	–	–	–	7.7
Hu24 76B	–	2.1	7.3	34.5	–	–	3.7	12.7	0.2	–	7.2	17.2	–	–	–	15.1
UR ES 343A	–	2.4	5.4	29.0	–	–	3.0	14.4	–	–	6.0	24.4	–	–	–	15.4
UR ES 343B	–	1.7	6.6	29.3	1.2	–	3.9	15.3	–	–	6.8	5.2	–	–	12.6	17.5
Hu24 76A	–	2.2	8.0	33.5	–	–	3.7	14.1	–	–	14.4	4.9	–	–	–	19.2
UR WS 342F	1.0	3.3	17.1	26.6	0.4	–	4.9	8.4	–	–	3.7	6.9	–	–	–	27.6
HuA1 31	0.4	0.8	7.0	34.1	–	–	2.7	5.8	1.1	–	7.3	11.1	–	–	–	29.7
CP 344A	–	1.9	5.4	32.3	2.0	–	3.3	12.4	0.9	–	10.8	9.3	–	–	–	21.7
CP 344B	–	2.5	1.6	29.6	2.3	–	2.9	12.9	1.1	–	10.0	11.4	–	–	–	26.1
Hu24 77A	–	1.6	4.2	24.3	–	–	0.8	11.1	0.4	–	8.0	18.5	–	–	–	31.2
HuA1 27A	–	1.6	5.3	22.2	–	–	3.1	11.4	–	0.4	13.4	11.1	–	–	–	31.5
Reverberatory Slags-Type II (Average of 5 samples)	–	–	3.3	24.4	0.4	4.2	1.1	1.3	–	0.3	13.0	19.0	0.8	0.1	–	32.0
UR WS 342C	–	1.3	7.5	26.9	–	3.1	3.6	6.7	–	–	4.8	12.7	–	–	–	33.4
HuA1 26C	–	0.7	6.2	23.5	–	1.1	2.8	8.3	–	–	4.9	15.5	2.8	–	–	34.2
HuA1 26B	–	1.0	4.8	23.6	–	–	1.6	8.2	0.3	–	4.9	13.4	–	–	–	42.2
UR WS 342B	0.5	0.4	7.9	29.8	–	2.9	4.1	3.8	–	–	2.4	4.4	–	–	–	43.7
UR WS 342G	–	1.3	5.1	21.2	–	–	2.1	9.2	–	–	3.1	6.2	–	–	–	51.9
Hu24 77B	–	1.7	3.3	19.1	–	–	0.7	11.7	0.7	–	5.2	5.4	–	–	–	52.3
HuA1 29	0.8	–	8.2	30.5	–	–	2.4	1.0	–	–	1.6	–	1.0	1.8	–	52.7
UR ES 343C	–	1.2	4.8	19.4	–	–	1.9	7.8	–	–	3.1	4.0	–	–	–	57.7
DMD Slag 341A	–	0.4	2.8	22.2	–	–	1.2	4.2	–	–	3.2	5.9	–	–	–	60.1
Reverberatory slags-Type I (Average of 8 samples)	–	–	2.6	20.0	–	–	0.6	0.8	–	0.1	6.8	3.6	–	0.5	–	65.0
UR WS 342A	0.2	–	0.8	8.8	–	12.4	0.2	1.8	–	–	7.5	2.6	–	–	–	65.7
UR ES 343D	–	0.6	5.2	10.8	–	–	–	1.4	–	–	1.0	13.9	–	–	–	66.4

\*The data has been normalised to 100wt% and sorted by the lead oxide content. Sample codes relate to the archaeological sites: Hu24 = Huayrachina site 24, HuA1 = Huayrachina Alta, UR WS = Uruquilla West Saddle, UR ES = Uruquilla East Saddle, CP = Cruz Pampa, DMD = Dragon furnace slag sample.

*Los datos han sido normalizados a 100% en peso y ordenados por el contenido de óxido de plomo. Códigos de ejemplo se refieren a los sitios arqueológicos: Hu24 = sitio Huayrachina 24, HuA1 = Huayrachina Alta, UR WS = Paso Uruquilla Oeste, UR ES = Paso Uruquilla Este, CP = Cruz Pampa, DMD = muestra escoria horno "dragón".*

The architectural layout of Uruquilla and its association with provincial Inka ceramics suggest that it had been constructed under the Inkas, perhaps to house mining personnel. However, the site continued to be used into the Colonial Period.

Three furnaces located at the foot of Cerro Huayna Porco and to the southeast of the residential complex at Uruquilla were excavated in 2005 (fig. 10). These features appeared only as burned, fire-reddened patches on the surface; no building materials or slag were evident, probably because of the intensive gleaning and recycling that have occurred at the site over

the centuries. Excavations revealed the foundations of three reverberatories in varying states of preservation: UR10, UR11 and UR12 (fig. 11).<sup>4</sup> They are arrayed in a line and built on the same surface, suggesting that they are roughly coeval. The best preserved furnace, UR11, was constructed on a rectangular base measuring approximately 3 by 2.5 m. The furnace consists of a circular hearth that is approximately 1.6 m in diameter, a rectangular fire box located on the northeast side of the hearth, and an extension on the southeast that may be the base of a chimney. Instead of having a grate, the floor of the firebox is perforated by a series of holes



Figure 10. Foundations of three reverberatory furnaces excavated at Uruquilla (UR10, UR11 and UR12).

*Figura 10. Cimientos de tres hornos de reverbero excavados en Uruquilla (UR10, UR11 y UR12).*

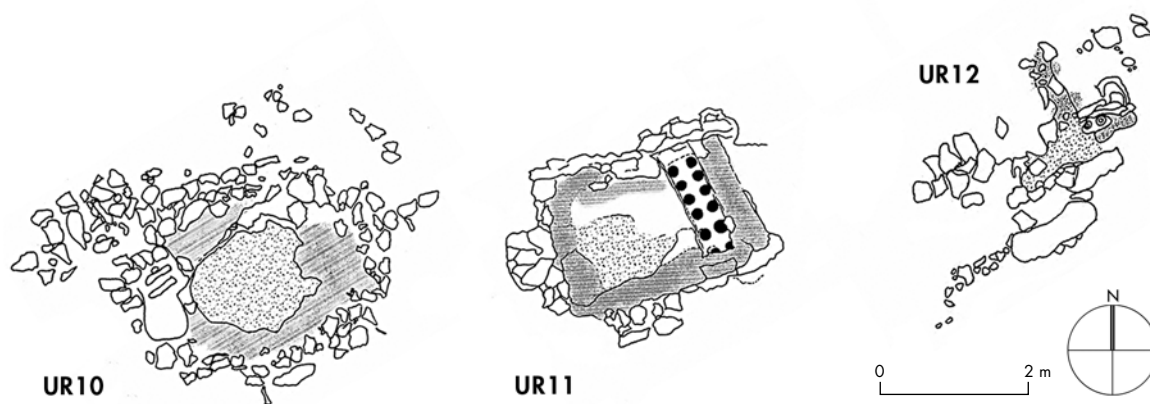


Figure 11. Plan of three reverberatory furnaces excavated at Uruquilla (UR10, UR11 and UR12).

*Figura 11. Plano de tres hornos de reverbero excavados en Uruquilla (UR10, UR11 y UR12).*

(fig. 12). The outer walls of the platform are composed of local stone, while the inner walls were constructed of adobe. With the exception of the firebox floor and

the possible absence of a chimney, the plan of UR11 is identical to the domed reverberatory illustrated by Alonso Barba (1992 [1640]).





Figure 12. View of UR11 showing opening for removing ashes from perforated firebox.

*Figura 12. Vista del UR11 mostrando la abertura que servía para quitar cenizas de la caja de fuego perforada.*

The foundation of UR10 is also fairly well preserved (fig. 13). It measures approximately 3 by 3.5 meters and is oval in plan. Like UR11, a circular hearth is at the center of the furnace, and a rectangular firebox is attached to one side. Unlike UR11, an adobe grill was constructed at the base of the firebox. Archaeomagnetic samples were collected from the hearth by Jeffrey Eighmy in 2005. These were compared to a newly established curve and provided a date of 1675 to 1760, slightly later than was estimated on the basis of the small number of artifacts recovered during excavation (Lengyel et al. 2010). UR12 is located just to the east of UR11, but is very poorly preserved. Only part of the firebox, which has a perforated floor like that of UR11, was intact.

Samples were also collected from an unexcavated dragon furnace (the DMD site) located near a rural homestead to the northwest of Porco. This reverberatory furnace is undated, but the owner of the property indicated that it had not been used in his or his parents' lifetimes. The furnace includes a circular hearth measuring 1.2 m in diameter enclosed by a partially intact domed

roof in which two openings are located. A rectangular firebox is attached to one end of the hearth and an inclined chimney on the other.

A total of 19 samples of slag from these furnaces were analyzed using optical microscopy, SEM-EDS, and XRF: one from the DMD site, eleven from UR10, four from UR11, and three from UR12. These slag samples are highly vitreous, and many have ripple and flow lines on the exterior. All are lead silicates containing lead and zinc sulphides and metallic lead prills. The overall slag matrix contains variable quantities of heavy metals such as iron, zinc, arsenic, and antimony, but zinc and iron oxides are common to all. Two primary types can be distinguished by the relative quantities of lead and zinc that are present. These types are not correlated with different furnaces but instead result from the acquisition of ore from slightly different veins. The presence of sulfur in the majority of the metallic prills indicates that the lead ore was sulphidic, probably lead sulphide, and the high levels of lead in the slag and silver in the metallic prills suggest the production of a silver-lead alloy.





Figure 13. Excavation of UR10 at Uruquilla.

Figura 13. Excavación del sitio UR10 en Uruquilla.

Thus like *buayrachinas*, the reverberatory furnaces appear to have been used to smelt unroasted argentiferous galena, which produced a lead-silver bullion that required further refining. These results indicate that rather than being linked in a single chain of production, *buayrachinas* and reverberatories were used for the same purpose.

## TECHNOLOGICAL VARIATION AND LONG TERM CHANGE

One obvious explanation for the co-existence of *buayrachinas* and large reverberatories is that they represent distinct technological styles associated with different cultures, in the first case *yanaconas* and other native Andeans, and in the second Europeans or *mestizos*. Smelters would produce and use the kind of technology with which they were most experienced and could also rely on their social networks for technical information and ritual knowledge as well as materials

such as firewood, lead and other inputs. While this may be largely the case for *buayrachinas*, which appear to be closely associated with small-scale smelting by indigenous producers, the same cannot be said of the larger reverberatory furnaces. The latter were erected in public places and indigenous workers were most likely involved in their construction and operation, forming part of a technological “community” (Schiffer 2002) that had the opportunity to learn about them. In at least one case, the DMD site described above, a domed reverberatory was also employed for smelting at an indigenous estancia. In addition, small reverberatories that were used as cupellation hearths were incorporated into the technological repertoires of indigenous households, and, as we shall discuss below, used on a semi-industrial scale for the refining of silver by native producers in nineteenth century Peru. So, in the long term the close connection between these technologies and users of particular ethnic origins broke down as indigenous people learned about and modified reverberatory furnaces for their own purposes.

While the cultural identity of users was undoubtedly important in the choice of technologies, particularly early in the Colonial Period, two other factors—which relate to but cannot be reduced to ethnic origin—may have been important as well: the scale of production and the cost of inputs. Because of the way they are oxygenated, *buayrachinas* cannot be significantly increased in size without impairing their functionality. In contrast, reverberatory furnaces, which use either bellows or a natural draft created by a chimney, can be increased in size to accommodate larger quantities of ore. The drawback, however, is that unlike *buayrachinas*, they require large quantities of firewood, the preferred fuel for such furnaces (Alonso Barba 1992 [1640]: 136; González 1995), which would have increased the cost of operation considerably.<sup>5</sup> Medium-sized producers—perhaps Europeans, but also *mestizos* and native Andeans—would have both the need and the means for using this type of technology.

Interestingly, over time indigenous people also seem to have downsized reverberatories and modified them for incorporation into the domestic economy. The small cupellation hearths used in conjunction with *buayrachinas* to produce silver in many of the estancias around Porco are functionally identical to the cupellation hearths described by European metallurgists (Agricola 1950 [1556]: 469–475, Biringuccio 1990 [1540]: 162–165), and morphologically similar to the domed reverberatories described by Alonso Barba (1992 [1640]) and found in the archaeological record. Their diminutive size, however, makes them suitable for refining small quantities of ore, and they are fired with camelid dung, an abundant local resource.

The earliest cupellation hearth of this type was found during excavation and yielded an archaeomagnetic date of 1650 to 1775 (Lengyel et al. 2010).<sup>6</sup> Unlike the others identified during survey it was constructed in a small metallurgical complex (Site 35) that is visible from the road. The majority of dated cupellation furnaces are located near rural estancias that were occupied during the nineteenth or twentieth centuries. This pattern suggests that the use of cupellation hearths may have been associated at first with the processing of ores that were legitimately acquired, perhaps by *k'ajchas*, workers who were allowed to mine high quality ore during the weekends or who “share-cropped” veins that were owned by others (Rodríguez Ostria 1989; Tandeter 1993; Platt 2000). When Bolivian and foreign companies began to invest in mining in the late nineteenth and early twentieth centuries, they attempted to suppress *k'ajcheo* in an effort to control the labor force and increase profits. However, the removal of high grade ores by workers has continued up to the present, an activity that is now

known as “*jukeo*” and one that mine owners regard as theft. The occurrence of cupellation hearths near isolated nineteenth and twentieth estancias is most likely related to the refining of ores that were illicitly obtained from capitalist enterprises.

The cupellation hearths in Porco are small and were used in domestic settings, but very similar furnaces were employed by indigenous people on a much larger scale in Cerro de Pasco, Peru, in the nineteenth century (Pfordte 1893). Like those in Porco, they consisted of a round hearth with a firebox on one side and a chimney on the other. They were constructed of fire-proof stone lined with clay and enclosed within a thatch-roofed structure. Fuel consisted primarily of dried llama dung, although coal and bituminous shale were used as well. These furnaces were employed to refine argentiferous galena and gray copper, as well as ruby silver and argentite when available. Unlike at Porco, however, hundreds of kilos of ore were refined at a time.

The differentiation of reverberatory technology that we describe here is, of course, a tentative history. In particular, the relationship between early *tocochimbo*s and the cupellation hearths used today in conjunction with *buayrachinas* is unclear. While there is some evidence for cupellation in pre-Hispanic times (Schultze et al. 2009), no information about the technology used to accomplish this has yet been published. In order to develop a more robust reconstruction of the history of metallurgy in the southern Andes, we clearly need well-dated evidence of fifteenth century antecedents—both Andean and Spanish.

## CONCLUSION

The great variety of smelting and refining technologies seen in the archaeological record of Porco during the first half of the Colonial Period is due to the continued use and modification of small-scale smelting technology. Unlike Potosí, Porco did not have sufficient water for powering a stamp mill and, with the exception of Antonio López de Quiroga's construction of a large adit in the 1670s, mining was practiced on a small scale during the seventeenth and eighteenth centuries (Bakewell 1988: 73).<sup>7</sup> These factors inhibited the adoption of mercury amalgamation and created conditions in which smelting technology not only persisted but was further developed. In the late nineteenth and early twentieth centuries, the technology that was best suited for processing very small quantities of high grade mineral—*buayrachinas* and cupellation hearths—was adopted by households whose members occasionally produced silver from

ores that they illicitly obtained while working in mines owned by large companies. Other smelting technologies, particularly the reverberatory furnaces used by small, independent producers, were abandoned.

The history of reverberatories that we have tentatively reconstructed on the basis of archaeological and historical evidence traces the ways in which a single technology introduced from Europe was incorporated into different social contexts. Reverberatory furnaces were modified for a variety of purposes—to smelt ore from medium-size workings in both public and domestic contexts, to refine illicitly acquired silver at home, and to produce silver on a semi-industrial scale. While scholars have increasingly focused on Andean mining and metal-working in pre-Hispanic times, this research demonstrates that indigenous people continued to play a creative role in the metallurgical sector, not just as laborers, but also as the inventors and users of new technology.

**ACKNOWLEDGEMENTS** The archaeological work on which this investigation is based was conducted by the Proyecto Arqueológico Porco-Potosí directed by Mary Van Buren. Funding for research at Porco has been provided by the National Endowment for the Humanities (RZ-20934-02), the National Science Foundation (BCS-0235954), the National Geographic Society, the H. John Heinz III Charitable Trust, and the Curtiss T. and Mary G. Brennan Foundation. Thanks to the Institute of Materials, Minerals and Mining (IOM3) for funding Claire Cohen's Ph.D. research through the awarding of the Stanley Elmore Fellowship, and to the Institute for Archaeo-Metallurgical Studies, the UCL Institute of Archaeology, the Heide Stolz Fellowship, and Río Tinto Plc for their financial sponsorship. We are also grateful to Kevin Reeves, Philip Connolly and Simon Groom for their laboratory advice and to Dimitris Stevis for his constant support. Brendan Weaver graciously provided the map of Porco. Special thanks go to Ludwing Cayo, Delfor Ulloa, Edwin Quispe, and the many residents of Porco who have worked on field crews over the years, and especially to Carlos Cuiza who taught us about smelting and refining. Three anonymous reviewers provided useful comments that helped us improve the final paper.

## NOTES

<sup>1</sup> Recent historical research suggests that the Inka not only knew about the silver deposits in Cerro Rico of Potosí, but established an important shrine to the Sun on its summit (Salazar-Soler 1997a; Platt & Quisbert 2008). Cruz's archaeological study (Cruz & Absi 2008) of the area has revealed the presence of pre-Hispanic metallurgical activity, but no clear evidence of Inka mining and metallurgy.

<sup>2</sup> Téreygeol and Castro's (2008) analysis of the residue on crudely made ceramics associated with *buayrachina* remains at Juku Huachana, a site in Potosí, indicates that the vessels were used to scorify the bullion prior to cupellation, and scorifiers have also been found at Porco, although not in direct association with *buayrachinas*. Schultze and collaborators (2009) have recovered evidence of scorification at a pre-Hispanic silver processing locale in the Titicaca Basin. This intermediate step between smelting and cupellation is not described in the colonial documents.

<sup>3</sup> According to Graulau (2008) Anton Fugger received a license from the Spanish Crown for "colonizing Chile and southern Peru" in 1532, and in 1535 a representative was in Chile overseeing the Fugger's investment in the slave trade. This connection may have

provided a direct conduit for the introduction of mining technology into the southern Andes.

<sup>4</sup> While the superstructures of these furnaces were not intact, the similarity of the bases and fireboxes to other, well preserved furnaces with domed roofs in the Porco area strongly suggests that the Uruquilla furnaces were also domed.

<sup>5</sup> Large furnaces can be fueled with llama dung as accounts of early twentieth century metallurgy on the Altiplano indicate (Miller & Singewald 1916). However, the fireboxes of the reverberatory furnaces in Porco were clearly constructed to hold firewood, as dung, and even charcoal, would have fallen through the perforations in the firebox floor. Yareta could also have been employed, but even this fuel would have become expensive as local sources were depleted (Miller & Singewald 1916).

<sup>6</sup> This cupellation hearth contained a glass bead and a fragment of a copper hawkbell, objects that are commonly found at sixteenth and early seventeenth centuries sites and which suggest that the hearth may have been used earlier than the archaeomagnetic date indicates.

<sup>7</sup> We refer here to the mines in Cerros Huayna and Apo Porco. As we mentioned earlier, a stamp mill was constructed in the eighteenth century on the San Juan River 7 km to the southwest of Porco and probably processed ore extracted from the Sora Sora mines (Weaver 2008).

## REFERENCES

- ACOSTA, J., 1954 [1590]. *Historia natural y moral de las Indias*. Madrid: Ediciones Atlas.
- AGRICOLA, G., 1950 [1556]. *De re metallica*. Translated by H. C. Hoover & L. H. Hoover. New York: Dover.
- ALONSO BARBA, A., 1923 [1640]. *Arte de los metales*. Translated by R. E. Douglass & E. P. Mathewson. New York: John Wiley & Sons.
- 1992 [1640]. *Arte de los metales en que se enseña el verdadero beneficio de los de oro, y plata por azogue, el modo de fundirlos todos y cómo se han de refinar, y apartar unos de otros*. Madrid: Consejo Superior de Investigaciones Científicas.
- ASSADOURIAN, C. S., 1992. Base técnica y relaciones de producción en la minería de Potosí. In *Ciencia colonial en América*, A. Lafuente & J. Sala Catalá, Eds., pp.121-142. Madrid: Alianza Editorial.
- BAKEWELL, P., 1984a. *Miners of the Red Mountain: Indian Labor in Potosí, 1545-1650*. Albuquerque: University of New Mexico.
- 1984b. Mining in Colonial Spanish America. In *The Cambridge History of Latin America*, Vol. II, L. Bethell, Ed., pp. 105-151. Cambridge: Cambridge University Press.
- 1997. Technological Change in Potosí: The Silver Boom of the 1570's. In *Mines of Silver and Gold in the Americas*, P. Bakewell, Ed., pp. 57-77. United Kingdom: Ashgate Publishing.
- BIRINGUCCIO, V., 1990 [1540]. *The Pirotechnia of Vannoccio Biringuccio: The Classic Sixteenth Century Treatise on Metals and Metallurgy*. Translated and edited by C. S. Smith & M. T. Gnudi. New York: Dover.
- CAPOCHE, L., 1959 [1585]. *Relación general de la villa imperial de Potosí*. Madrid: Ediciones Atlas.
- CASTILLO MARTOS, M., 1994. Primeros beneficios de la plata por amalgamación en la América colonial (1565-1600). In *Minería y metalurgia. Intercambio tecnológico y cultural entre América y Europa durante el período colonial español*, M. Castillo Martos, Ed., pp. 375-406. Seville / Bogotá: Muñoz Moya / Montraveta Editores.
- CASTILLO MARTOS, M. & M. F. LANG, 1995. *Metales preciosos: Unión de dos mundos. Tecnología, comercio y política de la minería y metalurgia Iberoamericana*. Seville / Bogotá: Muñoz Moya / Montraveta Editores.
- CIEZA DE LEÓN, P., 1984 [1553]. *La crónica del Perú*. Madrid: Historia 16.



- COHEN, C., 2008. The Winds of Change: An Archaeometallurgical Study of Silver Production in the Porco-Potosí Region, Southern Bolivia, AD 1500-2000. Ph.D. dissertation, Institute of Archaeology, University College London.
- COLE, J., 1985. *The Potosí Mita, 1573-1700: Compulsory Indian Labor in the Andes*. Stanford: Stanford University Press.
- CRAIG, A. K., 1993. The Ingenious *Ingenios*: Spanish Colonial Water Mills at Potosí. In *Culture, Form, and Place: Essays in Cultural and Historical Geography, Geoscience and Man* 32, K. Mathewson, Ed., pp. 125-156. Baton Rouge: Geoscience Publications, Louisiana State University.
- 1994. Spanish Colonial Silver Beneficiation at Potosí. In *In Quest of Mineral Wealth: Aboriginal and Colonial Mining and Metallurgy in Spanish America, Geoscience and Man* 33, A. Craig & R. West, Eds., pp. 271-285. Baton Rouge: Geoscience Publications, Louisiana State University.
- CRUZ, P. & P. ABSI, 2008. Cerros ardientes y buayras calladas. Potosí antes y durante el contacto. In *Mina y metalurgia en los Andes del Sur desde la época prehispanica hasta el siglo XVII*, P. Cruz & J. J. Vacher, Eds., pp. 91-120. Sucre: Institut de Recherche pour le Développement / Instituto Francés de Estudios Andinos.
- GARAVAGLIA, J. C., 2000. Plata para el Rey. Tecnología y producción en el Potosí colonial. In *Potosí: Plata para Europa*, J. Marchena Fernández & J. Villa Rodríguez, Eds., pp. 125-140. Seville: Universidad de Sevilla / Fundación El Monte.
- GÓMEZ DE CERVANTES, G., 1944 [1599]. *La vida económica y social de Nueva España al finalizar el siglo XVI*. Biblioteca Histórica Mexicana de Obras Inéditas 19. Mexico: José Porrua e Hijos.
- GONZÁLEZ, L. R., 1995. Recursos y organización de la producción metalúrgica prehispánica en la región centro sur: un caso de estudio. *Hombre y Desierto* 9: 213-223, Antofagasta.
- GORDON, R. & R. KNOPF, 2007. Late horizon silver, copper and tin from Machu Picchu, Peru. *Journal of Archaeological Science* 34: 38-47.
- GRAULAU, J., 2008. Finance, Industry, and Globalisation in the Early Modern Period: The Example of the Metallic Business of the House of Fugger. *Rivista di Studi Politici Internazionali* 300: 554-598.
- HOWE, E. & U. PETERSON, 1994. Silver and Lead in the Late Prehistory of the Mantaro Valley, Peru. In *Archaeometry of Pre-Columbian Sites and Artifacts: Proceedings of a Symposium Organized by the UCLA Institute of Archaeology and the Getty Conservation Institute, Los Angeles, CA, March 23-27, 1992*, D. A. Scott & P. Meyers, Eds., pp. 183-198. Malibu: Getty Conservation Institute.
- KILLICK, D., 2004. Social constructionist approaches to the study of technology. *World Archaeology* 36 (4): 571-578.
- LENGYEL, S.; J. EIGHMY & M. VAN BUREN, 2010. Archaeomagnetic research in the Andean highlands. *Journal of Archaeological Science*. DOI 10.1016/j.jas.2010.08.021.
- MILLER, B. L. & J. T. SINGEWALD, 1916. Substitutes for Coal in the Andes. *Coal Age* 9: 1040-1043.
- MIRA, G., 2000. Panorama de la organización y las bases de la producción de plata en Potosí durante el período colonial (1545-1825). In *Potosí: Plata para Europa*, J. Marchena Fernández & J. Villa Rodríguez, Eds., pp. 105-124. Seville: Universidad de Sevilla / Fundación El Monte.
- NEFF, J. U., 1941. Silver Production in Central Europe, 1450-1618. *The Journal of Political Economy* 49: 575-591.
- OCAÑA, D., 1969 [1608]. *Un viaje fascinante por la América hispana del siglo XVI*, Fr. Arturo Álvarez, Ed. Madrid: STVDIVM Ediciones.
- OEHM, V. P., 1984. *Investigaciones sobre minería y metalurgia en el Perú prehispánico*, Bonner Amerikanistische Studien 12. Bonn: Universität Bonn.
- PFORDTE, O., 1893. Ancient method of silver-lead smelting in Peru. *Transactions of the American Institute of Mining Engineers* 21: 25-30.
- PLATT, T., 2000. Señorío aymara y trabajo minero. De la *mita* al *k'ajcheo* en Potosí (1545-1837). In *Potosí: Plata para Europa*, J. Marchena Fernández & J. Villa Rodríguez, Eds., pp. 189-211. Seville: Universidad de Sevilla / Fundación El Monte.
- PLATT, T.; T. BOUYSSÉ-CASSAGNE, O. HARRIS & T. SAIGNES, 2006. *Qaraqara-Charka: Mallku, Inca, y Rey en la provincial de Charcas (siglos XV-XVII): Historia antropológica de una confederación aymara*. La Paz: IFEA-Plural Editores.
- PLATT, T. & P. QUISBERT, 2008. Tras las huellas del silencio. Potosí, los Inkas y el virrey Toledo. In *Mina y metalurgia en los Andes del Sur desde la época prehispanica hasta el siglo XVII*, P. Cruz & J. J. Vacher, Eds., pp. 231-277. Sucre: Institut de Recherche pour le Développement / Instituto Francés de Estudios Andinos.
- PRESTA, A. M., 2008. La primera joya en la corona en el Altiplano Surandino. Descubrimiento y explotación de un yacimiento minero inicial: Porco, 1538-1576. In *Mina y metalurgia en los Andes del Sur desde la época prehispanica hasta el siglo XVII*, P. Cruz & J. J. Vacher, Eds., pp. 201-229. Sucre: Institut de Recherche pour le Développement / Instituto Francés de Estudios Andinos.
- RAMÍREZ, B., 1965 [1597] *Descripción del reyno del Perú*. In *Relaciones geográficas India: Perú*, Vol. II, M. Jiménez de la Espada, Ed., p. 119. Madrid: Biblioteca de Autores Españoles, Ediciones Atlas.
- RODRÍGUEZ OSTRIA, G., 1989. *Kajchas*, trapicheros y ladrones de mineral en Bolivia (1824-1900). *Siglo XIX. Revista de Historia* 4 (8): 125-139.
- SALAZAR-SOLER, C., 1997a. Las huacas y el conocimiento científico en el siglo XVI: a propósito del descubrimiento de las minas de Potosí. In *Saberes y memorias en los Andes: In memoriam Thierry Saignes*, T. Bouysse-Cassagne, Ed., pp. 237-258. Paris-Lima: IHEAL/IFEA.
- 1997b. Socavones de mestizaje: saberes, técnicas y trabajo en la Villa Imperial de Potosí (siglos XVI-XVIII). In *Ciudades mestizas: Intercambios y continuidades en la expansión occidental. siglos XVI a XIX. Actas del Tercer Coloquio Internacional de Mediadores Culturales*, C. García Aylluardo & M. Ramos Medina, Eds. pp. 271-302. Mexico City: Centro de Estudios de Historia.
- 2002. Innovaciones técnicas, mestizajes y formas de trabajo en Potosí de los siglos XVI y XVII. In *O Traballo Mestiço. Maneiras de Pensar e Formas de Viver Séculos XVI a XIX*, E. França Paiva & C. M. Junho Anastasia, Eds., pp. 141-159. São Paulo: Annablume.
- SCHIFFER, M., 2002. Studying technological differentiation: The case of 18<sup>th</sup> century electrical technology. *American Anthropologist* 104 (4): 1148-1161.
- SCHULTZE, C.; C. STANISH, D. SCOTT, T. REHREN, S. KUEHNER & J. FEATHERS, 2009. Direct evidence of 1,900 years of indigenous silver production in the Lake Titicaca Basin of southern Peru. *Proceedings of the National Academy of Sciences* 106 (41): 17280-17283.
- SERRANO, C., 1994. Intercambio tecnológico en la amalgamación entre los centros mineros de América con sus homólogos europeos. In *Minería y metalurgia. Intercambio tecnológico y cultural entre América y Europa durante el período colonial español*, M. Castillo Martos, Ed., pp. 407-436. Seville and Bogotá: Muñoz Moya y Monraveta Editores.
- SERRANO, C. & J. PELÁEZ, 1992. Potosí y su sistema hidráulico. *Boletín de la Sociedad Geográfica y de Historia Potosí* 14 and 15.
- TANDETER, E., 1993. *Coercion and Market: Silver Mining in Colonial Potosí, 1692-1826*. Albuquerque: University of New Mexico Press.
- TÉREYGEOL, F. & C. CASTRO, 2008. La metalurgia prehispánica de la plata en Potosí. In *Mina y metalurgia en los Andes del Sur desde la época prehispanica hasta el siglo XVII*, P. Cruz & J. J. Vacher, Eds., pp. 11-28. Sucre: Institut de Recherche pour le Développement / Instituto Francés de Estudios Andinos.

- VAN BUREN, M., 2003. Un estudio etnoarqueológico de la tecnología de fundición en el sur de Potosí, Bolivia. *Textos Antropológicos* 14 (2): 133-148. La Paz: Universidad Mayor San Andrés.
- VAN BUREN, M. & B. H. MILLS, 2005. *Huayrachinas* and *tocochimbos*: Traditional smelting technology of the southern Andes. *Latin American Antiquity* 16 (1): 3-25.
- VAN BUREN, M. & A. M. PRESTA, 2010. The organization of Inka silver production in Porco, Bolivia. In *Distant Provinces in the Inka Empire: Toward a Deeper Understanding of Inka Imperialism*, M. Malpass & S. Alconini, Eds., pp. 173-192. Iowa City: University of Iowa Press.
- WEAVER, B., 2008. Ferro Ingenio: An Archaeological and Ethnohistorical View of Labor and Empire in Colonial Porco and Potosí. M. A. Thesis, Department of Anthropology, Western Michigan University, Kalamazoo.