# Current silver smelting in the Bolivian Andes: a review of the technology employed

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*ABSTRACT: Recent ethnographic studies by Proyecto Arqueológico Porco-Potosí of traditional silver smelting in the southern Andes have revealed the continuing use of huayrachinas, peculiar small wind-blown furnaces. This technology was believed to have become extinct at the turn of the 20th century. Historical literature cites the huayrachinas as being an indigenous technology local to the Bolivian Andes. This paper is an overview of the historical and ethnographic records of huayrachina use throughout the last 500 years. It also contains initial results of analyses from a current smelting site. The paper focuses on the history and technological efficiency of the huayrachina.*

## Introduction

The Proyecto Arqueológico Porco-Potosí was established by Dr Mary Van Buren to help illuminate the history of silver production and aid further understanding of the history and technology of the Porco-Potosí region of the Southern Bolivian Andes (Fig 1; Van Buren and Mills 2005). Project personnel have recorded the current use of *huayrachinas*, wind powered furnaces, a practice which was last described in 1893 (Peele 1893, 9) and since assumed to be extinct. *Huayrachinas* are thought to have stemmed from pre-colonial, native Andean roots; however, no conclusive evidence for this is known at present, and the issue is one of the foci of our current research. The *huayrachina* is a perforated natural draught furnace that uses wind to aid smelting. It has a cylindrical shaft, normally less than a metre tall, that is pierced with series of holes allowing ventilation from the wind. It can be used to smelt lead and/or silver ores. According to historical sources *huayrachinas* are always found in high and windy areas (Van Buren and Mills 2005). The word *huayrachina* comes from Quechua; *huayra* meaning wind and *chi* the causative and *na* transforms the word into a noun. It is often translated as being 'the place where the wind blows through'. The word *huayrachina* also means the winnowing of grain. Colonial literature cites different spellings and names of wind blown furnaces: guayra, guiara, huayra. In this paper the term *huayrachina* is used throughout with the exception of citations from historical sources. Proyecto Arqueológico Porco-Potosí's investigation has established that *huayrachina* usage has continued in the region and the examination of current practices should aid in the understanding of pre-Hispanic metallurgy. This paper outlines a brief history of the use of *huayrachinas* in the Bolivian Andes and describes the current production of silver as a basis upon which to understand and interpret archaeological smelting remains.

## The history of the Porco-Potosí region

In the early 16th century the Spanish conquered large parts of NW South America and made them into the vice-royalty of Peru. The *conquistadores* were confronted by the Incas, whose empire covered an area from modern day Ecuador to parts of northern Chile and Argentina. The Inca Empire was highly centralized, with a supreme ruler governing from Cuzco in what is now modern-day Peru. However, while provinces were controlled by Inca officials, conquered populations were generally


*Figure 1: Map of Bolivia showing the location of Potosí and Porco.*

allowed to live in relative freedom and to practise their own customs and traditions (Moseley 2001). During, and probably prior to the Inca conquest, the Department of Potosí in Bolivia was occupied by members of the Charcas confederation, a loose alliance of ethnic groups, and under the Spaniards the region became part of the Audiencia of Charcas. Much of the area lies at very high altitude (over 4000m), and is characterized by sparse vegetation with very few trees or shrubs. The soils are not particularly fertile, agriculture is difficult, and herding of *camelids* (today mostly llamas) is a major source of income and dominates land use patterns in rural areas. The economic importance of this region is based on different riches; it is believed that this province played an important role in Inca mining and silver production. In 1538 Charcas was invaded by the *conquistadores*, the Inca domination of the area crumbled, and Spanish rule began.

The Spanish did not immediately discover the ore deposits of Potosí. Legend has it that only in 1545 were the mineral veins of Potosí discovered by an Indian who told his Spanish master that the *Cerro Rico* (Rich Mountain) had a wealth of silver ore hidden within (Fig 2). This was seven years after the village of Porco, which is 50km SW of Potosí, had been established as a Spanish mining centre. Mining and extraction was already being carried out there since at least 1538. New World authors such as Capoche (1585) and Alvaro Alonso Barba (Douglass and Mathewson 1923) consider Porco to be of Inca origin. Bakewell (1984) summarises that most

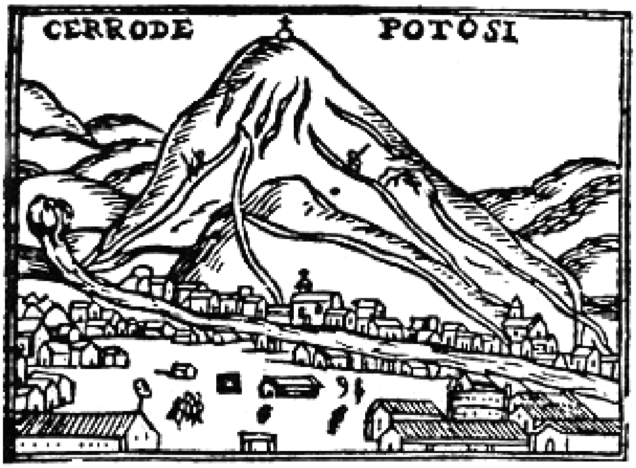


*Figure 2: A depiction of the Cerro Rico, Potosí, in the 17th century (after Bakewell 1984).*

workers who were employed in the mines of Potosí came from Porco and as such this implies that Porco preceded Potosí as a mining region.

## Smelting technology from the colonial era onwards

*Huayrachinas* were the predominant furnace type used to smelt silver until 1570, when Francisco de Toledo, the fifth viceroy of Peru, introduced a new technique, mercury amalgamation. This enabled the extraction of silver from medium to low grade ores that previously would have been unsuitable for smelting (Bakewell 1997). The patio process required considerable capital investment and organization, strengthening direct Spanish control over the mining sector. The Spanish also restarted the system employed by the Incas of using forced workers (Craig 1994). However, the widespread adoption of mercury amalgamation did not completely eradicate the use of *huayrachinas*, and small scale usage continued, probably primarily within indigenous households.

The Colonial authors provide insights into early colonial Potosí but generally they do not provide detailed description of the processing of silver. There are a few exceptions; Alvaro Alonso Barba's treatise *Arte de los Metales* (Douglass and Mathewson 1923), first published in 1640, is comparable to the works by Agricola (Hoover and Hoover 1950), Ercker (Sisco and Smith 1951) and Biringuccio (Smith and Gnundi 1959), all of whom discuss metal production in the Old World. However, *Arte de los Metales* was written 100 years after the conquest so the description of pre-Hispanic practices may be severely distorted. Barba discusses the *huayrachinas*, which he calls *guayras*, stating that: 'The natives of this country, who have not yet gotten to

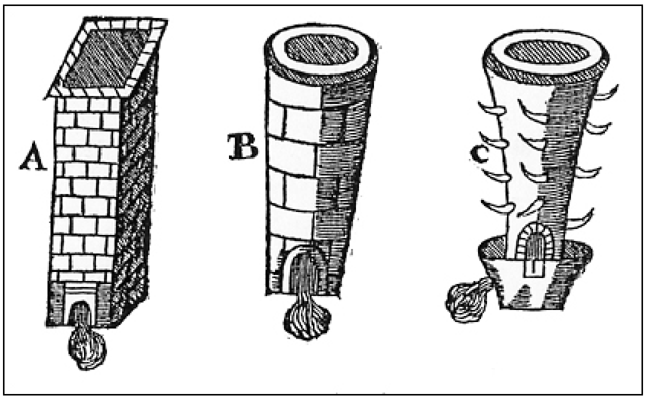

*Figure 3: Alvaro Alonso Barba's illustration of three furnaces used for smelting rich ores. A) the European furnace, B) the Castellano (Spanish) furnace, and C) the guaira or indigenous furnace (after Douglass and Mathewson 1923, 199).*

the point of using our Bellows, employ, for smelting, furnaces called *Guayras* (Wind Furnaces); the same are still used in this Imperial Village, and in many other parts.' (Douglass and Mathewson 1923, 198).

Barba compares three smelting furnaces: the European, the *Castellano* and the indigenous *guayra* (Fig 3). His illustration of the *guayra* shows the holes used for ventilation and he states they were used in areas where strong winds constantly occur and notes they did not require bellows. These wind-blown furnaces could have been used in conjunction with other refining features to further process the smelted metal.

Barba's observation of the use of *huayrachinas* in early colonial Bolivia is not the first report: Luis Capoche (1585) writes that many *guairas* were positioned around the village of Potosí, where they lit the mountain from the late afternoon and through the night. 'Llegó los años pasados el número de los asientos de guairas a seis mil cuatrocientos y noventa y siete. En este tiempo permanecen casi todos, aunque están arruinados gran parte de ellos, por no usarse la guaira como solía.' (Capoche 1585, 11) [In past years, the number of *guaira* sites reached 6,497. Most of them have remained throughout this time although are ruined because the *guaira* is no longer used the way it used to be (Claire Cohen's translation)].

The practice of smelting in the *huayrachinas* at night was probably to obtain maximum wind to power the furnaces, and with the lowest possible fuel required. In the Andes, specifically in the altiplano region, the wind is stronger in the late afternoons.

The most recent report is by Robert Peele Jr (1893), who described the process of silver production in the southern Andes as current in his day; he clearly states that the use of a *huayrachina* was common practice among the Indians of Potosí. He says: '…it has an extremely small capacity, and is wholly unsuited to modern requirements, still, as a survival of the times of the Incas, it possesses some interest as a metallurgical curio' (Peele 1893, 9). Peele comments on the mineral that was being used in the smelt: 'The materials treated are galenas, as well as zinc-blende and pyretic combinations, and those containing the high-grade sulphides, such as ruby silver, gray copper, silver sulphide, etc' (Peele 1893, 9). He also states that in place of galena, litharge could be used and this was collected from 'native refining furnaces'. Peele's report was the last documented evidence for this technique, which was subsequently believed to have become extinct.

The refining furnaces mentioned by Peele are probably comparable to those referred to earlier by Barba, who mentions the use of *tocochimbos,* indigenous furnaces that are related to muffle furnaces used for assaying. Unfortunately no further information is given about these *tocochimbos*, and it is uncertain whether Andean silver production outside the patio process was always based on a two-step process of smelting to give a lead-silver bullion and subsequent refining by cupellation to obtain pure silver, or whether the ore was initially rich enough to be smelted directly to silver, and the cupellation represents a European technology introduced after the conquest. Unfortunately, the historical sources are even more silent on cupellation than on *huayrachina* smelting.

In conclusion, historical documentation shows the *huayrachina* being used as a part of silver production from the point of colonisation in the 1530s. The majority of written sources after this point claim that it is of native Andean origin although this has yet to be archaeologically proven. Clearly, exploitation of minerals for smelting was done on a relatively large scale, as is obvious from historical reports; but where is the archaeological evidence? How were the indigenous people of Porco producing lead and silver metal? How did the practice continue after amalgamation was introduced? The historical literature provides an excellent basis on which to study material debris, but it has left unanswered questions of technological choice and function, which this paper will address with reference to current *huayrachina* usage.

## Current silver smelting using *huayrachinas*

In 2001 Proyecto Arqueológico Porco-Potosí personnel identified a retired miner, Carlos Cuiza, who still uses

*Figure 4: The huayrachinas are situated on a ridge that allows for constant air flow, perfect for wind-blown furnaces.*

traditional smelting techniques and who agreed to have the process documented. Cuiza said that he learned how to use the *huayrachinas* from his parents who used similar furnaces to produce silver and sold it to the mint in Potosí (Van Buren and Mills 2005); currently he sells his silver privately to jewellers in Potosí. It should be noted that Cuiza is more or less regularly smelting and producing silver using techniques learnt from his parents; his activity is not an artificial reconstruction of an extinct technique but a continuation of traditional knowledge. His *huayrachinas* sit on a saddle in the ridge above his house (Fig 4) and are used three to four times a year to supplement his normal income. They are 860mm high, have an internal height of 450mm, and sit on top of four or five base stones (Mills 2003). They have twelve small apertures and two larger openings on opposing sides (Fig 5). It became apparent that Cuiza used a two stage process to produce pure silver: initial smelting of galena (PbS) using *huayrachinas* followed by refining of a high grade silver ore, using the lead produced in stage one, on a hearth within an indoor reverberatory furnace. This refining process is referred to as cupellation and produces a waste product called cupellation hearth material (CHM). CHM is litharge (pure lead oxide) absorbed into hearth lining made from plant ash. Cuiza owns two *huayrachinas*, but one works better than the other and in 2002 and 2003 only one was selected for use.

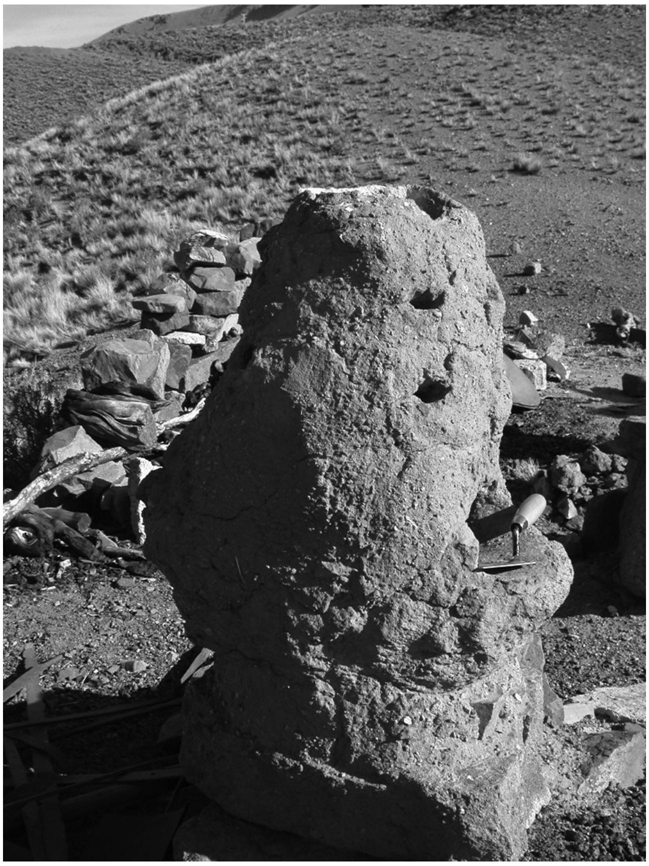

*Figure 5: The huayrachina has two mouths, one on each side. There are twelve pierced holes for ventilation towards the top of the shaft.*

*Figure 6: The huayrachina in action. Lead is flowing from the tap hole at the bottom of the shaft onto a shallow iron dish (bottom right).*

*Figure 7: Carlos Cuiza attends to his smelt, topping up charge and when necessary feeding slag back into the huayrachina.*

A total of seven smelts were documented in 2001, 2002 and 2003. For the smelts to be recorded by the Proyecto Arqueológico Porco-Potosí, Cuiza requested that members of the Project team purchase the silver ore, while he provided the lead ore. The following is a summary of the smelting practice.

Initially Cuiza repaired any cracks or damage on the *huayrachinas*, as they are made from local un-tempered clay and are prone to cracking. It was not necessary to let these fillers dry before the smelt. Cuiza beneficiated his lead ore by crushing it to fragments of about 10mm in diameter and sorting the pure galena from the gangue minerals. Gangue minerals were discarded and left on the ground close to the site. He also prepared lumps of CHM which he obtained from his own refining hearth (see below), but also from other hearths elsewhere in the vicinity of Porco. For the smelting process he used a mixture of charcoal prepared by him from *queñua* wood, and *churqui* charcoal which he bought in Potosí. He loaded the charge (beneficiated galena wetted with urine, CHM and charcoal) into the top of the *huayrachina*; no pre-heating stage using charcoal only was recorded. Once full the *huayrachina* was lit using *ichu* grass (a spiky grass that grows at high altitude), and the tap hole at the base of the *huayrachina* was plugged with a *queñua* stick (Fig 6).

Once the furnace was ablaze Carlos Cuiza attended to the smelt topping up with alternating layers of charcoal and beneficiated ore and CHM (Fig 7). Occasionally, molten lead was allowed to flow out of the tap hole, and Cuiza patiently waited while small quantities of lead metal ran from a hole at the base onto an iron dish. The smelting process lasted up to eight hours, but this was highly dependent on the weather conditions as the *huayrachinas* are reliant on strong constant winds to blow them and to maintain the temperature in the smelting chamber. During the smelt Cuiza performed *ch'allas*, symbolic ritual blessings, using coca leaves that were fed into the furnaces and libations of alcohol. Pieces of slag were removed from the two opposing mouths of the *huayrachina*. Cuiza continuously assessed the slag and decided whether it needed to be re-smelted and thus was thrown back into the furnace or had had the majority of lead removed. When the slag appeared less viscous it could be thrown away (Mills 2003, 16). The result of the *huayrachina* smelt was a quantity of pure lead tapped from the base of the furnace, and larger quantities of irregular lumps of slag scattered around the base.

The lead metal thus produced was then used to extract silver from rich ore. Cuiza has two cupellation furnaces, one that has been used for three generations and the second that was built in the last twenty years during a dispute with his brother. The older furnace works better and thus was usually selected by Cuiza to refine his silver. The cupellation furnace consists of three elements: the main chamber which holds a concave hearth, a fire box that is positioned to one side and slightly below this, and a chimney on the opposite side of the hearth. The furnace uses natural draft to carry the heat and flames from the firebox over the hearth and through the chimney out of the furnace structure. The hearth is lined with plant ash made from *llareta (Azorella yareta)* (Van Buren and Mills 2005), a moss-like plant native to the altiplano. Chemical analysis of this ash indicates that it consists of about one-third calcium oxide, one-third silica, about ten percent potash, just under ten percent alumina, and two-to-five percent each magnesia, iron oxide, soda and sulphate, and around one percent phosphorous oxide. The plant ash was wetted with urine and packed into the hearth, 20cm thick. The ash acts like a sponge and absorbs the liquid litharge formed during the cupellation process. The fire box was prepared and loaded with llama dung and *thola* wood. The lead was placed on the hearth through an opening at the top of the chamber which was then closed and the fuel in the fire box lit. Once the lead had melted, Cuiza briefly removed the door from one of the side openings of the central chamber and added finely-ground silver ore with an iron spoon. The whole process took up to nineteen hours while Cuiza continued adding llama dung and stoking the firebox and adding as much of the powdered ore as possible. At the end, a button of pure silver remained on top of a reacted cupellation hearth material (CHM) that can be removed from the hearth and used in the next *huayrachina* smelt as part of the charge.

Aspects of the procedure highlighted some of the super-

*Table 1: Inputs and outputs for all seven documented smelts (weights in kg, urine volume in litres)*

| Smelt No | 2001: 1 | 2001: 2 | 2002: 1 | 2002: 2 | 2003: 1 | 2003: 2 | 2003: 3 |
|---|---|---|---|---|---|---|---|
| Inputs | | | | | | | |
| Lead Ore | 12 | 14 | 12 | 11 | 10 | 14 | 16 |
| Litharge | 7 | 8 | 6 | 6 | 6 | 11 | 13 |
| Urine | 0.5 | 0.5 | 0.5 | 0.5 | unspecified | 0.75 | 1.5 |
| Charcoal | 12 | ? | 8 | 8 | 15 | 16 | 10 |
| Outputs | | | | | | | |
| Lead Metal | 4.34 | 6 | 4 | 5 | 2 | 2.5 | |
| Slag | ? | ? | 9 | 7 | 9 | 16 | |

*Smelt 2003: 3 used only 19kg of the 29kg of ore/litharge mixture that was prepared.*
*Data is from Mills 2003, Van Buren 2001, Van Buren 2003a, Van Buren 2003b and Van Buren and Mills 2005.*

stitions and beliefs that are associated with metallurgical processes. While smelting in the *huayrachina* Cuiza was happy for anyone to participate and ask questions but during the cupellation he was secretive and would only allow those people who had been present during the smelt to attend the refining. He was nervous of people talking too loudly within the chamber as he said the silver would become jealous (Mills 2003).

## Assessment of current silver smelting

A complete metallurgical analysis of Carlos Cuiza's silver smelting technique is currently underway as part of the doctoral research of the first author. Here, we will concentrate first on the quantification of material flow as recorded in 2001 to 2003 (Mills 2003; Van Buren 2003b; Van Buren 2001) and then characterize the metallurgical aspects of the smelts and the subsequent silver extraction.

Results so far suggest an interesting pattern. The first four smelts, recorded in 2001 and 2002, all operated with a ratio (by weight) of galena to CHM in the charge of around 2:1, and a fuel-to-charge ratio of around 1:2. With this, Cuiza produced around 5kg of lead metal from a typical charge of *c*20kg and using *c*10kg fuel (Table 1). We assume a lead metal content in the ore of 80% and in the CHM of 50%; from this we estimate each charge to contain between 12 and 15kg total lead metal. Thus, the overall metal yield in the *huayrachina* is around 30–40% (Table 2).

*Table 2: Pb efficiency within the furnace. The first five rows display kg values.*

| Smelt No | 2001: 1 | 2001: 2 | 2002: 1 | 2002: 2 | 2003: 1 | 2003: 2 | 2003: 3 |
|---|---|---|---|---|---|---|---|
| Total input of charge | 19 | 22 | 18 | 17 | 16 | 25 | 19 |
| Estimated Pb in PbS | 9.6 | 11.2 | 9.6 | 8.8 | 8 | 11.2 | 8.3 |
| Estimated Pb in PbO | 3.5 | 4 | 3 | 3 | 3 | 5.5 | 4.2 |
| Lead input to furnace | 13.1 | 15.2 | 12.6 | 11.8 | 11 | 16.7 | 12.5 |
| Lead output | 4 | 6 | 4 | 5 | 2 | 2.5 | 2 |
| Output as % of input | 31 | 39 | 32 | 42 | 18 | 15 | 16 |

Note: Smelt 2003:3 is pro rata

In 2003 however, the ratios differed from those used in the previous years. The proportion of CHM in the charge increased considerably, as did the fuel consumption (Table 1). For smelt 3, Carlos Cuiza initially mixed 16kg lead ore, 13kg CHM and 1.5 litres of urine, but due to bad luck credited to a visitor he only smelted 19kg of the above mixture (Van Buren 2003a); this has been taken into account in the calculations in Tables 2 and 3. Despite substantially unchanged total charge weights of around 20kg, and on average considerably higher fuel-to-charge ratios (Table 3), all smelts in 2003 were far less successful, producing only half the amount of lead as in previous years. This was attributed by Carlos Cuiza to poor ore and wind conditions.

## Interpretation

An initial review of the data indicates that the lead smelting process is not very efficient for metal yield, but may have other inherent benefits. Cuiza uses a mixture of galena and CHM as his charge, he is thus not only extracting the lead present in the galena but also recycling the lead within the CHM from previous smelts. However, almost two-thirds of the lead content of the charge are still lost in the process, either as fumes

*Table 3: Consumption of charge and fuel for all seven documented smelts (weights in kg)*

| Smelt No | 2001: 1 | 2001: 2 | 2002: 1 | 2002: 2 | 2003: 1 | 2003: 2 | 2003: 3 |
|---|---|---|---|---|---|---|---|
| Total input of charge | 19 | 22 | 18 | 17 | 16 | 25 | 19 |
| Charcoal | 12 | ? | 8 | 8 | 15 | 16 | 10 |
| Ratio fuel:charge | 0.63 | ? | 0.44 | 0.47 | 0.94 | 0.54 | 0.53 |
| Ratio fuel:lead output | 3 | ? | 2 | 1.6 | 7.5 | 7.2 | 5 |

and dust, or absorbed onto the furnace wall, but mostly discarded as solid slag lumps rich in lead silicate and lead sulphide and metal inclusions.

In 2003 the ratio of ore and CHM dropped to nearer to 1:1, and the quantity of lead extracted dropped to a yield of only 15 to 20% of the input, *ie* only half of the yield obtained in 2001/2002. It is possible that not only the ore quality and environmental conditions cited by Carlos Cuiza played a role in this, but also the changed balance between ore and CHM. We may assume that ideally the lead oxide from the CHM reacts with the lead sulphide from the ore to form lead metal and sulphur dioxide, but little slag. However, this co-smelting model would appear unnecessary in a furnace such as the *huayrachina* which in itself already provides ample oxygen to facilitate successful reduction of an un-roasted sulphidic ore. Lead oxide is highly reactive and will chemically react with any siliceous material, including the furnace wall, thus leading to the formation of large quantities of lead-rich slag, and a low yield of lead metal. Further increasing the CHM proportion in this system will probably lead to even more slag, and inevitably to an increased lead metal loss. It is difficult to ascertain whether the increased fuel consumption documented for the first two smelts in 2003 reflects an active response by Carlos Cuiza to the unsatisfactory lead production as noted already during the smelting, or results from different behaviour of the *huayrachina* under insufficient wind conditions. Whatever the case, it clearly did not help improve the metal yield.

Closer inspection of the situation in a *huayrachina* reveals that the temperature and redox conditions will be highly dependent on the location; if closer to the holes in the furnace shaft the ore will be under highly oxidizing conditions but will also experience higher temperatures. Thus within the furnace several reactions are occurring: the transformation of lead sulphide mineral into lead oxide, but equally possible is lead sulphide conversion to pure lead metal and, if lead oxide is present without siliceous material to react with, and is inside the furnace with sufficient carbon monoxide to drive the reduction, that too can be reduced to form lead metal:

$$2PbS + 3O_2 = 2PbO + 2SO_2$$
$$PbS + 2PbO = 3Pb + SO_2$$
$$PbO + CO = Pb + CO_2$$

All of these reactions are represented in the very heterogeneous slag samples of the recorded smelts.

The presence of large amounts of lead sulphide in a lead-silicate-rich slag matrix from the earlier smelts (Fig 8) indicates that the system was on the whole not strongly oxidizing, so while we must pay attention to the location within the furnace where the slag has formed we cannot deny that the system displays a highly sulphurized environment. If the conditions had been more oxidizing more sulphur would have been burned away; whether this would result in higher lead metal production or simply increased formation of lead silicate in the slag would depend on the exact circumstances in the *huayrachina*. The compositional analysis of the slag from the earlier smelts shows that while the furnace clearly yields some lead metal, the slag still contains consider-

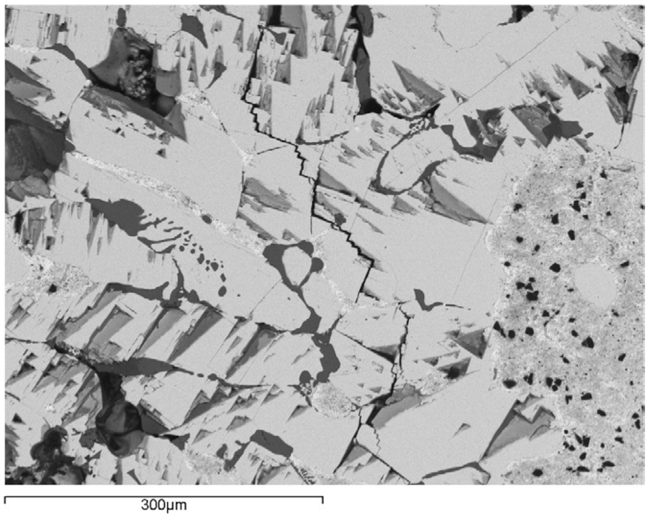


*Figure 8: BSE image of huayrachina slag showing recrystallised lead sulphide (note characteristic triangular patterning) with interstitial zinc sulphide phases (mid grey rounded inclusions). The lead sulphide was only partial molten during the smelt but some areas were transformed from lead sulphide into lead metal (dappled grey, bottom right). Silicon carbide crystals (dark grey) from the polishing process are embedded in the soft lead metal.*

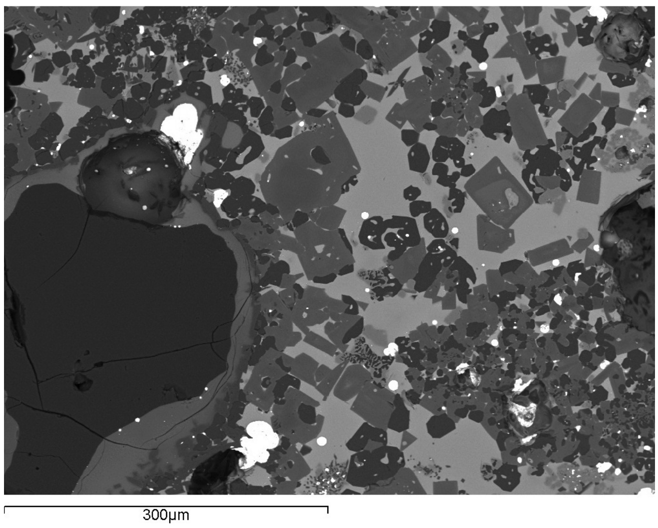


*Figure 9: BSE image of heterogonous huayrachina slag. A large quartz grain (dark grey) can be seen bottom left. Prills of lead sulphide (white), copper iron sulphide and zinc sulphide scatter the area. Olivines and leucite crystals (mid grey) sit within a glassy iron-rich matrix (light grey).*

able quantities of lead, both chemically bonded as lead silicate and mechanically trapped as lead sulphide and lead metal aggregates. Figure 9 illustrates slag from a *huayrachina*; it contains more than six different phases, the phases themselves being indicative of the initial ore source: recrystallized PbS, $CuFeS_2$ and ZnS are still visible as distinct phases within a complex slag base. Also apparent is the heterogeneity of most slag lumps as regards the redox conditions preserved in them, and the insufficient separation of the sulphides from the silicate melt, indicating insufficient operating temperatures and incomplete liquefaction of the charge.

Work is ongoing to test whether the different ratio of ore to CHM in the 2003 smelts and the increased fuel consumption resulted in a systematically different slag, possibly with more chemically bonded lead and, due to possibly higher temperatures and increased fluidity of the slag, less mechanically trapped lead sulphide.

The cupellation furnace differs from traditional European designs in that it is much more enclosed and is operated with a low-grade but cheap fuel. The addition of rich silver ore separately to the lead bath, rather than processing the silver ore with the primary smelting step and then de-silvering argentiferous lead metal, is well known from European practice when rich silver ores which did not have much lead mineral with them were processed. Due to the arrangement whereby the team, rather than Carlos Cuiza, bought the silver ore in Potosí, we have no fully-reliable data concerning the nature or quality of silver ore normally used by Carlos Cuiza himself; our ore samples did contain sufficient quantities of lead to make direct smelting feasible, but was not very rich and hence produced far less silver metal than expected. Further work is ongoing to explore this variable more fully. However, in view of the generally low lead metal yield in the *huayrachina* smelting of only around one third of the metal input, it makes perfect sense to charge the silver ore at the much better controlled cupellation stage rather than earlier.

A possible controlling factor is the quantity and quality of fuel used throughout the process. Comparative data on fuel consumption in lead smelting seems to be absent from the literature. However, estimates for fuel-to-ore ratios usually appear to be much higher than those recorded here (*eg* Anguilano *et al*, this volume, for an experimental lead smelt in a reconstructed bole, using a ratio of around ten to one). Carlos Cuiza's fuel consumption is markedly lower, possibly reflecting the general scarcity of fire wood and charcoal in the Bolivian altiplano. The vast quantities (several tens of kilograms) of much less valuable llama dung which he used in the cupellation only underline this idea of fuel as the main limiting factor in governing smelting practice.

## Conclusions

The analysis and documentation of current smelting practices have shown that the *huayrachinas* do not yield high quantities of lead metal. However, they appear to have been optimized for fuel efficiency as well as using the power of the wind to provide adequate temperatures and furnace conditions. The altiplano region of Bolivia has a severe fuel shortage and most wood has to be imported from lower altitudes; creating a furnace that uses relatively little fuel is very sensible. The technology requires a relatively low capital investment for Carlos Cuiza; he already has his *huayrachinas* that require very little extra care, they only need replacing every 2–3 years. Although he has to buy some of the charcoal he uses for the *huayrachina*, he can prepare some charcoal and other necessary fuel from his farm, in particular the llama dung which is used in large quantities for the cupellation stage. Perhaps the main economic investment is the ore that is used to gain silver. Cuiza uses both lead ore and recycled CHM as a source of lead metal, enabling him to control the batch composition within the smelting charge. Furthermore, Cuiza continuously checks the appearance of the slag produced, using it to inform his decisions about whether to discard or re-feed it for further smelting, and possibly also regarding the amount of fuel needed. This provides an interesting opportunity to analyse the variable input factors within the smelting process; important factors are the degree of desulphurization during the smelt, and the degree of liquefaction and homogenization of the charge. At present, it appears that the *huayrachina* operates not at equilibrium conditions, but provides a wide range of oxidizing and reducing conditions and very variable temperatures. The limited metal yield probably has to be seen in conjunction with the cost of lead ore and charcoal bought for cash, and the effort necessary for Carlos Cuiza to procure CHM and other fuel.

The historical record suggests that the *huayrachina* is of indigenous origin. While this still has to be proven it is clear that it has survived the last 500 years and it is quite probable that it was used prior to the Spanish conquest. Ongoing research into archaeological *huayrachina* remains will aid understanding of this technology, and possibly its development over time. Several archaeological *huayrachina* sites near Porco have been selected and sampled for archaeometallurgical analysis, and the results will be interpreted in conjunction with the analyses done on current *huayrachina* material. Similarly, archaeological cupellation remains will be studied to obtain more insight into the earlier practice of silver refining at Porco. It is hoped that with time we will be able to understand more about the origins and development of the *huayrachina* and cupellation technology within the Bolivian Andes.

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