A MAJOR PREHISPANIC COPPER PRODUCTION CENTER IDENTIFIED AT COLLAHUASI, SOUTHERN TARAPACÁ ALTIPLANO (CHILE)

UN GRAN CENTRO PREHISPÁNICO DE PRODUCCIÓN DE COBRE IDENTIFICADO EN COLLAHUASI, ALTIPLANO SUR DE TARAPACÁ (CHILE)

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This work presents the results of a study of mining-metallurgical production in late pre-Hispanic times in the Collahuasi Mining District (Northern Chile), specifically examining the technology employed and changes in the scale of production. We focus on recent results obtained in a study of 50 pyrometallurgical furnaces identified at the Ujina 8 and Ujina 10 archaeological sites and their relation to Collahuasi 37, the metallurgical camp located in very close vicinity. This makes Ujina 8, Ujina 10, and Collahuasi 37 the largest pre-Hispanic copper production center in Northern Chile. Metallurgical and mineral evidences recovered from these sites were subjected to archaeometric analyses in order to determine the nature of the smelted ore, the complexity of the metallurgical processes used, and the composition of the copper metal produced.
The technology and organization of pre-Hispanic copper production observed at Collahuasi will be discussed in the context of pre-Inca and Inca mining-metallurgical systems already identified in northern Chile, especially in regard to the smelting technique and scale of production.
Palabras claves: Copper mining, copper smelting, wind furnace, Northern Chile, Collahuasi, Late Intermediate Period, Inca.

En este trabajo se exponen los resultados acerca de la producción minero-metalúrgica en momentos prehispánicos tardíos en el distrito de Collahuasi (norte de Chile) a partir de un estudio de la tecnología empleada así también como de los cambios de la escala de producción. Nos centraremos en los resultados recientes del estudio de las estructuras pirometalúrgicas de Ujina 8 y Ujina 10 y su relación con el campamento de metalurgistas situado en Collahuasi 37. Las estructuras pirometalúrgicas de Ujina 8 y Ujina 10 suman cerca de 50 unidades, constituyendo el sitio metalúrgico prehispánico más grande del norte de Chile. Por su parte, las evidencias metalúrgicas y minerales recuperadas fueron sometidas a distintos análisis arqueométricos con el objetivo de identificar los minerales reducidos, los procesos metalúrgicos y el cobre metálico producido. Los resultados del estudio de la tecnología y organización de la producción prehispánica del cobre en Collahuasi serán discutidos en el contexto de los sistemas de minero-metalúrgicos preincaicos e incaicos conocidos para la zona de estudio en términos de sus tecnologías y escalas de producción.
Key words: *minería de cobre, reducción metalúrgica, hornos de viento, Norte de Chile, Collahuasi, Período Intermedio Tardío, Inca.*

Minerals and metals were central to South Andean societies (Angiorama 2001; Lechtman 2014; Núñez 1987, 1999, 2006), being intensively exchanged in pre-Hispanic trade networks (Berenguer 2004; Browman 1984; Lecoq 1987, 1999; Nielsen 2003; Núñez and Dillehay 1979). From the Late Archaic

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period onward, and especially between the Formative and Inca periods, lapidary (Rees 1999; Soto 2010), pigment-making (Sepúlveda et al. 2014) and metal production (Figueroa et al. 2015; Lechtman and Macfarlane 2005; Maldonado et al. 2010; Salazar et al. 2011) created a considerable demand for copper minerals. Nevertheless, despite the influence of mining-metallurgical production on settlement systems, exchange practices, sociopolitical organization and ritualism of Northern Chile's pre-Hispanic populations, few archaeological studies to date have focused on the organization of pre-Hispanic copper metal and copper minerals production (Salazar and Vilches 2014). Little is also known about the relationship between the two production systems -mining and metallurgy-, or how they were articulated with major living places and/or administrative centers, pre-Hispanic road networks, distribution and redistribution networks for finished metal products.

The Collahuasi mining and metallurgical district offers a unique opportunity for investigating these topics from a holistic perspective (Shimada 1994; Shimada and Craig 2013). The zone under study is situated at 4500 masl, with little agricultural potential but major copper resources, and as such historically it has had no permanent human occupation, but was important for interregional traffic between Atacama, Tarapacá and the Bolivian Altiplano, in addition to being used as a mineral extraction and metallurgical site (Figure 1). The pre-Hispanic occupations that have been documented to date range from the Late Intermediate Period (LIP) (ca. AD 1000) to the Inca period (or Late period) (ca. AD 1450) and are systematically associated with mining and metallurgical evidences. Of special interest is the presence of a metallurgical campsite -Collahuasi 37- along with four major smelting sites-Ujina 8, Ujina 9 and Ujina 10, Ujina 11- in which more than 50 furnaces have been identified, along with copper ore, copper slags, prills and drops of smelted metal. Taken together, these sites constitute the greatest and most complex body of evidence of pre-Hispanic metallurgy known to date in Northern Chile. In this paper, we aim at reconstructing mining and metal production systems for the LIP and Inca periods in Collahuasi District, thereby expanding our knowledge of the variability and evolution of Andean metallurgy (Lechtman 2014). Following Salazar et al. (2013a) our investigation will be guided by an approach that includes the study of the organization of pre-Hispanic copper production based on the concept of mining-metallurgical landscape. This involves understanding mining and metal production systems in terms of their articulation with the economy, social organization and supply, transport and administrative systems. To engage with this perspective we employed complementary methods that included field surveying, extensive and test-pit excavations, as well as laboratory materials analysis, favoring an archaeometallurgical approach including mineralogical analysis (QEMSCAN), metallographic investigation (optical microscopy, SEM) and the study of elemental composition (SEM-EDX, PIXE).

New Information on the Late Periods in the Collahuasi Mining District

While studies of late periods in the Tarapacá Altiplano have been few, recently new information has accumulated complementing previous knowledge obtained through the study of sites such as Collacagua (Niemeyer 1962), Inkaguano-2 (Reinhard and Sanhueza 1982), Collahuasi 37 (Lynch and Núñez 1994; Romero and Briones 1999) and the area of Isluga (Sanhueza 1981; Sanhueza and Olmos 1981). For the LIP, investigators have recently identified major settlements high up in the central and northern Tarapacá Altiplano (Uribe et al. 2007), but with few permanent operations in the southern part, where Collahuasi District is located, very possibly owing to its very low agricultural potential and the extreme climate in the zone (Urbina 2012). Consistent with this pre-Inca panorama, a recent study of the Qapacñan (Inca Road) on the Tarapacá Altiplano reveals that the Incas deployed different strategies in that area, precisely depending on the pre-existing ethnic scenario and the interests of the Inca state in each sector (Berenguer et al. 2011). While the southern part of the Tarapacá Altiplano would have been directly incorporated into the Inca state, like the more northerly sector, in the former case it would have been primarily for the purpose of controlling caravan routes on the Huasco salt flat and for appropriating a pre-existing mining-metallurgical installation located at Collahuasi (Berenguer 2007; Berenguer and Cáceres 2008; Berenguer et al. 2011; Urbina 2012). Both the dates obtained from the settlement of Collahuasi 37 and the presence of pre-Inca ceramics at the site confirm that, in effect, a mining facility operated there during the LIP, very possibly for the extraction and processing of copper ores. Furthermore, that facility was later incorporated and transformed by the Incas to become part of their own political economy (Berenguer et al. 2011; Lynch and Núñez 1994; Salazar et al. 2013a; Urbina 2012). Nevertheless, further in-depth study is required on the origins of the Late Intermediate populations of Collahuasi and the transformations introduced in the production system after its incorporation into Tawantinsuyu. Given that this was an intermodal area between pre-Inca population centers of the Atacama (Berenguer 2004; Castro 2001; Castro et al. 2016; Uribe 2002), Lípez (Nielsen 2002),

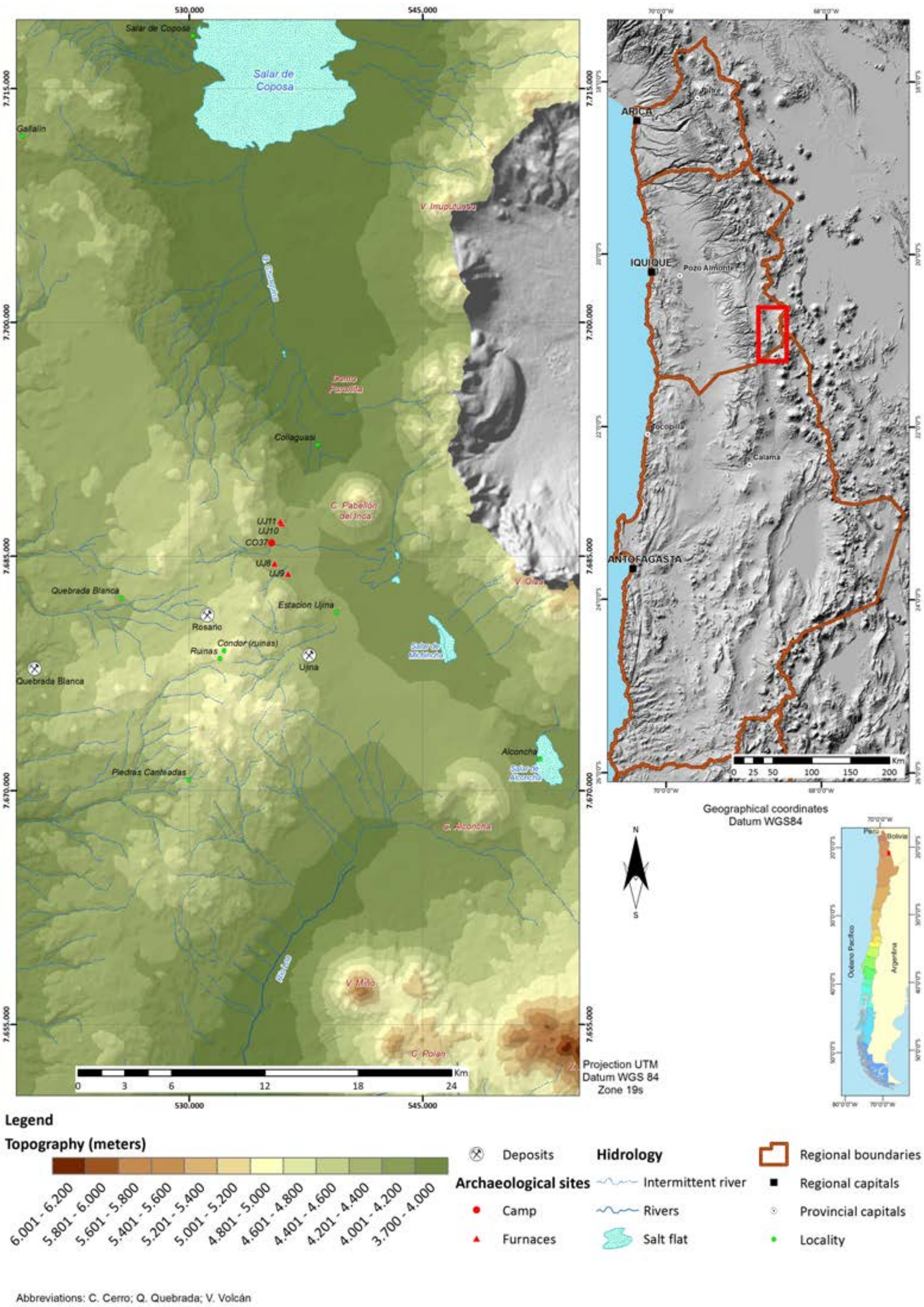

Figure 1. Map of the archaeological sites and the mining districts of Collahuasi.
Mapa de los sitios arqueológicos y los distritos mineros de Collahuasi.

Tarapacá (Uribe 2006) and "Intersalar" (Lecoq 1999) areas, it is important to determine whether in the pre-Inca period the sector was worked by multiple ethnic groups, or whether mining-metallurgical production was controlled by some of the ethnic groups mentioned. For its part, while the Inca presence in Yabricoyita or Collahuasi 37 is clearly proven by the high frequency of Local Inca, Provincial Inca and Polychromatic Cuzco ceramics, as well as by elements of the state architectural pattern and radiocarbon dates falling within the Late Period (Berenguer et al. 2011; Lynch and Núñez 1994; Romero and Briones 1999; Salazar et al. 2013a, 2013b; Urbina 2012), it is still necessary to examine in-depth the Inca transformations introduced at the site, as well as to understand how that site was part of a series of complementary settlements whose purpose was to reorganize copper production and introduce it into state-controlled circulation networks. In this regard, the most recent interpretations indicate that during the Late Period the site operated more as a mining-metallurgy production center than as a *tambo* (overnight rest stop) (Lynch and Núñez 1994; Romero and Briones 1999; Salazar et al. 2013a; Urbina 2012), and that the Inca administration would have put in place in Collahuasi District a model of spatial organization for production similar to that used in the Loa copper mining districts. In the latter, miners were concentrated in a residential camp that was set up to extract ores from a single major deposit (Salazar et al. 2013b), while on a sub-regional scale the productive enclave was articulated with other sites, including the Inca Road, *tambos* and administrative centers focused on religious worship, such as Cerro Colorado in the case of the San José del Abra Mining Complex, and Miño 1 in the case of Collahuasi (Salazar et al. 2013b). However, more information is needed to demonstrate the validity of this model outside the Alto Loa. In fact, at Collahuasi there are already indications of a more complex spatial organization, as the mining operations are not close the Co37 camp, as is the case of El Abra. In any case, it must be noted that differences between these productive systems may also be due to the fact that in Collahuasi, metallurgical production sites have been positively identified while they are virtually absent from the abovementioned Atacameño locality. The present study will enhance our understanding of the reorganization of Inca mining-metallurgical landscapes in the highlands of Northern Chile, based on a case that has been studied little but offers abundant.

Results

The aim of this investigation has been to understand the production systems in terms of their articulation with the economy, social organization and supply, transportation and administration systems of mining-metallurgical societies in the LIP and Late periods, paying special attention to the characteristics, continuities and transformations of these variables. In this paper we focus on the study of one of the district's most significant elements: the furnaces used to manufacture copper metal. In a recent project, four metallurgical production sites -Ujina 8, Ujina 9, Ujina 10 and Ujina 11- have been identified and more than 50 smelting furnaces identified within them, along with copper ore, slags and prills of copper metal.

Collahuasi 37 miner-metalworker camp

The metalworkers camp called Yabricoyita or Collahuasi 37 (Co37) has been studied by several researchers since the 1990s, and includes an RPC ("compound perimetral enclosure"), corrals, residential structures, public plazas and *collqas* (storage *silos*) (Berenguer et al. 2011; Lynch and Núñez 1994; Romero and Briones 1999; Salazar et al. 2013a; Urbina 2015) as well as abundant Provincial Inca and Polychrome Cuzco ceramic remains (Berenguer et al. 2011). Co37 is located 2 km from the Inca Road and connected to it by a side trail, and presents occupations from both the LIP and Late periods (Figure 2). Nearly 500 m south of the site are the sites of Ujina 8 and 9, and 700 m north are Ujina 10 and 11, all of which are metallurgical production areas with several stone furnaces and slag remains. Both the dates obtained from the Co37 settlement and the presence of pre-Inca ceramics at the Co37 site confirm that during the LIP a copper ore extraction and processing facility operated here. Following Urbina (2015), Co37 represents a mixed Inca site, with two types of components-one being the Inca architectural components represented in groupings A1, A2, C4, B3 and B5, the second corresponds to the sector D, E and F groupings and includes elements of the regional architectural tradition that we know was present in the Tarapacá highlands at least since the LIP. This project took an in-depth look at the nature of mining-metallurgical activities at Co37 by performing new excavations of the residential structures (B, D, and E sectors) and storage spaces (sector F) of Co 37. While the research team also had prior information about sector E, based on two pits in structure 12 that were interpreted as a metallurgical work area associated with residential structures and dated to the final years of the LIP, or even possibly the early Late period, that sector (sector E, structures 4, 8, 12, 13, 14, 15, 17) was excavated once again in order to obtain further information about its occupation and function, and above all a more precise chronology. Based on the materials studied in sector E, metallurgical activity appears to have centered around structures 8 and 12, which display the greatest concentration of slag and copper ores. Following Romero and Briones (1999) sector A was a residential sector of personnel specialized in administrative tasks or specific tasks with mining production, perhaps *altiplanic mitimaes* because it is separated from the agglutinated sets (Urbina 2015). Urbina (2015) describe sector D as a classical architectural regional tradition developed since the LIP in the highlands of Tarapacá, the Intersalar zone of Bolivia and the Altiplano. Recent excavations of sector D (structure 15) showed the reiterated presence of Pica-Tarapacá components from the LIP, in association with Inca components, especially from Taracapá, along with potential Altiplano-Inca expressions of the Saxamar type (Uribe 2017) which is consistent with the architectural analysis of Urbina (2015). Judging by the metallurgical evidence found during excavation of the stratigraphic layers, this area would have been a residential-production area. Additionally, sector F (structures 4, 5, 13, 26) was excavated to define its function. Briones and Romero (1999) had suggested that this sector might have corresponded to metallurgical furnaces, while Salazar et al. (2013b) interpret those same structures as possible storage units. Although little material was found in our excavations (bone fragments, ceramic sherds, and copper ore), these structures were not built for metallurgical activities and may have been used to store copper ore.

To date, it has not been possible to demonstrate the difference between sectors E and D, at either the chronological or productive level, except for a location in different sectors of Co37 camp. Based on the results documented for the examined structures and their associations, our hypothesis is that sector E corresponds to a residential area for staff specialized in certain metallurgical production tasks. Given this, a question arises regarding sector D's function and chronological relation to sector E. In other words, are we dealing with two diachronic residential-productive settlements, or two units operating contemporaneously in which the occupants were from two different ethnic groups?

In general, one can say that while there are elements suggesting a pre-Inca as well as Inca occupation of the camp, it has not been able to distinguish this diachronic sequence stratigraphically. What is observed is the great impact of the occupation associated with Tawantinsuyo, which would have led to the remodeling, modification, and cleaning up of the site and all of its architecture, resulting in the current version of the site. The systematic association of LIP and local and Provincial Inca ceramics denotes precisely such a possible scenario, in which the *tarapaqueños* and the previously-settled Altiplano groups coexisted under an Inca presence, with the former consisting of major contingents that performed mining-metallurgical work. While, as mentioned, it has been difficult to find pristine LIP contexts, there is more than a little evidence to support that hypothesis, including the existence of several LIP sites nearby, the existence of contemporaneous dates at Co37, local traditional architecture, and local ceramics. The radiocarbon dates associated with the furnaces of the Ujina sector are also coherent with a LIP occupation in Co37.

Copper resources and evidence of mining operations at Collahuasi

The locality of Collahuasi offers a unique scenario for investigating the district's mining-metallurgical production system. The mining district of Doña Inés de Collahuasi includes two deposits of Cu-Mo porphyry called Rosario and Ujina (Dick et al. 1994) within a 30 km long and 40 km wide horst of mesozoic and paleozoic rock that runs north to south (Bisso et al. 1998) and is part of the Upper Eocene-Oligocene metallogenic belt.

The Collahuasi andesites unit (PzTac) presents the most potential for mining metals in the area, especially copper oxides. In these deposits, the predominant mineralization is supergene and consists primarily of chrysocolla and malachite. In the northern sector of the study area, based on archaeological surveys near residential and metallurgical production sites in the Co37 andesites unit (PzTac), two work sites were found along with a seam 1 m thick and at least 10 m long, running N29E/30SE. In the sector containing mineshafts, the andesites present reddish-brown limonitic patinas, with epidote-chlorite alteration and silicification (Figure 3). Furthermore, shafts 1 and 2 are 140 m to 240 m, respectively, away from the Ujina 11 archaeological site, and 550 m and 680 m respectively, distant from the Ujina 10 archeological site. Their width varies, from 1 m (mineshaft 1) to 15 m (mineshaft 2), and their depth is estimated to be between 3 m (mineshaft 1) and 4 m (mineshaft 2). These shafts are almost vertical (Figure 4). To date, no evidence has been found that would enable us to confirm the dates these shafts were made, but they do provide food for thought regarding the possibility of working this kind of veinlet near the camp and metallurgical production centers.

Collahuasi's smelting furnaces (furnaces, slag heaps, ore, slag, fuel, wind)

In 2012, José Berenguer led an intensive survey of the Ujina area leading to the discovery of the Ujina 8 and Ujina 9 pre-Hispanic metallurgical sites. In 2015, an intensive investigation of the Ujina 8 hill was conducted to identify all traces of metallurgical production, while at the same time surveys were

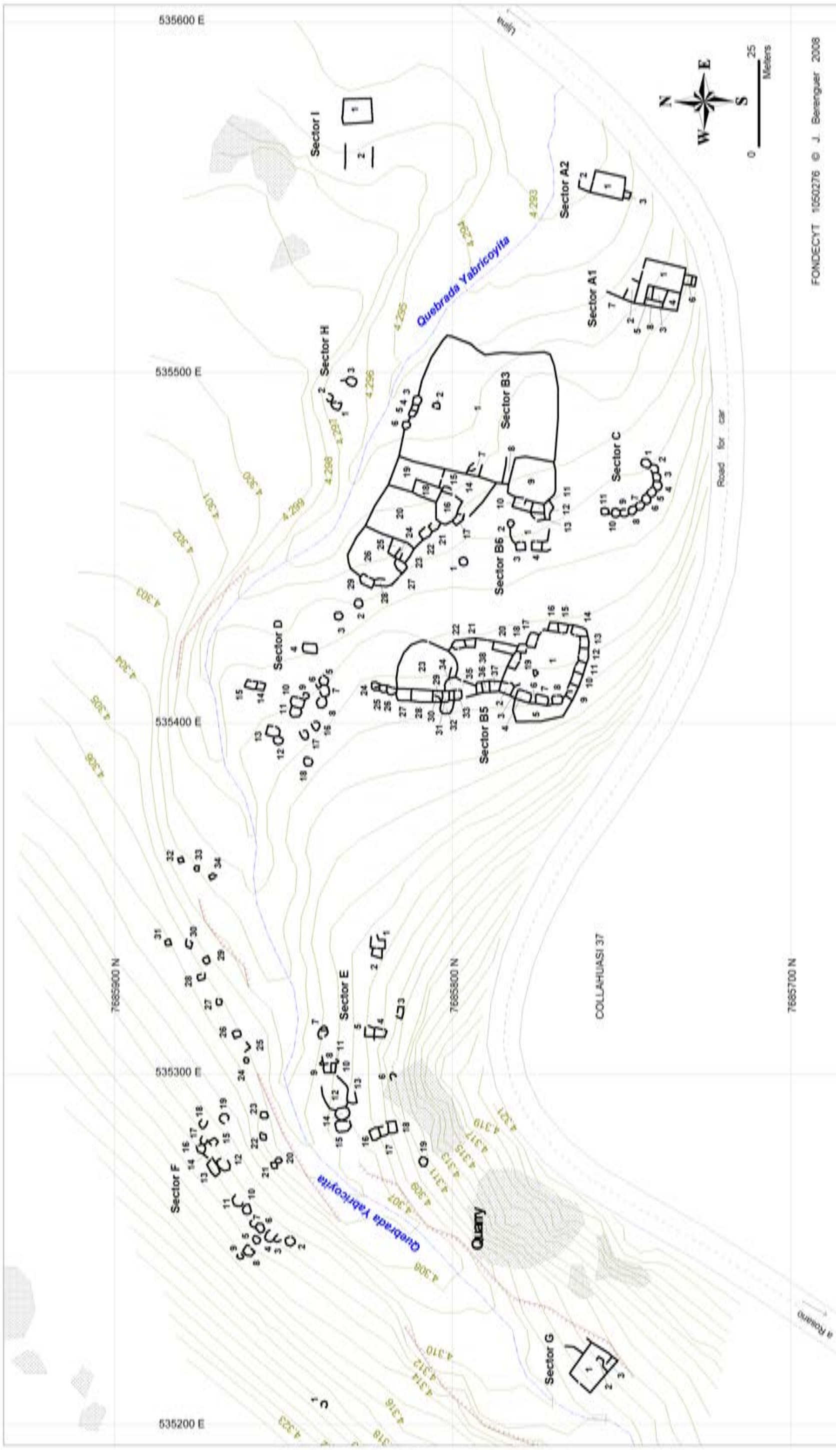

Figure 2. Collahuasi 37's site (Berenguer 2008).
Sitio de Collahuasi 37 (Berenguer 2008).

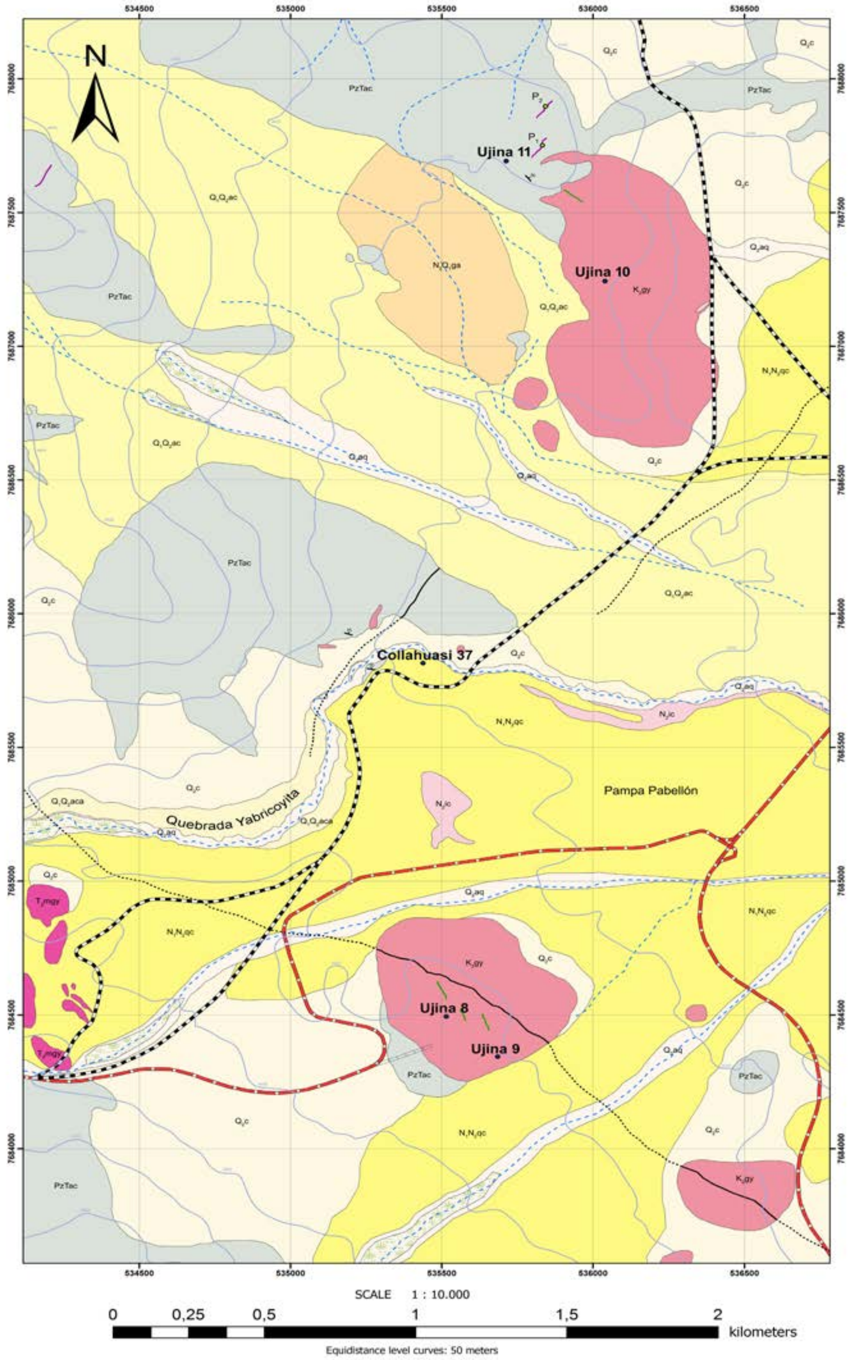

Figure 3. Geological map of the Collahuasi archaeological sector. The archaeological sites are found within three different rock formations, namely PzTac, K2gy y N1N2qc. Site Ujina 11 is found in PzTac (light green), which is a andesitic sequence; Ujina 8, Ujina 9 y Ujina 10 are found in K2gy (orange brown), which is a granodiorite intrusive; and Collahuasi 37 is found in N1N2qc (brown), which is a semi-consolidated clastic deposit. In addition, the P1 and P2 mining shafts have been found in the upper levels of PzTac, running N29E/30SE.

Mapa geológico del sector arqueológico de Collahuasi. Los sitios arqueológicos se encuentran en tres formaciones rocosas diferentes denominadas informalmente como: PzTac, K2gy y N1N2qc. PzTac (verde claro) corresponde a una secuencia de andesitas y sobre esta unidad se ubica el sitio Ujina 11, K2gy (rosado) es un intrusivo de granodioritas y sobre esta unidad se ubican los sitios Ujina 8, Ujina 9 y Ujina 10 y N1N2qc (amarillo) corresponde a depósitos clásticos semiconsolidados modernos y sobre esta unidad se ubica el sitio Collahuasi 37. Además, los piques mineros P1 y P2 se encontraron sobre niveles superiores de la unidad PzTac de dirección N29/30SE.

Figure 4. The width of the mineshafts varies, from 1 (mineshaft 1) to 15 (mineshaft 2) meters, and their depth is estimated to be between three (mineshaft 1) and four (mineshaft 2) meters (for safety reasons the researchers could not descend into the shaft). These shafts are almost vertical.

El ancho de los piques mineros varía de 1 m a 15 m (mina 2), y su profundidad se estima entre 3 m (minas 1) y 4 m (minas 2) (por razones de seguridad los investigadores no pudieron descender al eje). Estos ejes son casi verticales.

expanded to cover other similar areas, leading to the discovery of three additional metallurgical sites in the area-Ujina 10, Ujina 11 and Ujina 12. This intensive survey determined that the Ujina area comprised at least 50 production units with evidence of pre-Hispanic smelting furnaces (Figure 5).

These production units systematically included two related types of features: (1) smelting furnaces only made of dry stone, without any clay. At Ujina-8, 9, 10, 11 and 12, the furnaces have a typical bench shape and are made with granodiorite blocks (Figure 6). Some furnaces are built upon flat boulders, other upon naturally occurring rock benches with additional stones arranged to form the structure. From one to the other, the overall shape of the furnaces may vary, and it may be possible in the future to distinguish several subtypes. But all share common features, particularly a significant length (4 m to 10 m), an orientation perpendicular to the dominant wind, and a back wall of a height not exceeding 10 cm (Figure 7). The granodiorite blocks were assembled to form a base where the fuel and the ore were put, while the back wall allowed to hold the charge in position even with a very strong wind. (2) Slag heaps: these are areas of varying size with a very high concentration of metallurgical slags on the ground. Each furnace was generally linked to a unique slag heap, which was located in close vicinity, but always a few meters away, in a place well protected from the wind (Figure 8). Hammers and grinding stones have also been found associated with the slag heaps, giving clear evidence of crushing activities occurring there.

The remains found in production units are typical of a copper smelting activity and can be classified into five separate categories-copper ore fragments, fuel remains, copper metal, copper slags and crushing tools. It should be noted that ore pieces, metal prills and slags are not only found at the Ujina production sites, but also at the residential site of Co37, where no evidence of furnaces has been recorded. In the paragraphs below we will present some of our results, in the following order: (a) ores; (b) slags; (c) copper metal; (d) tools; (e) fuel; (f) wind. We include this last "resource" given its key importance in local metallurgical activities.

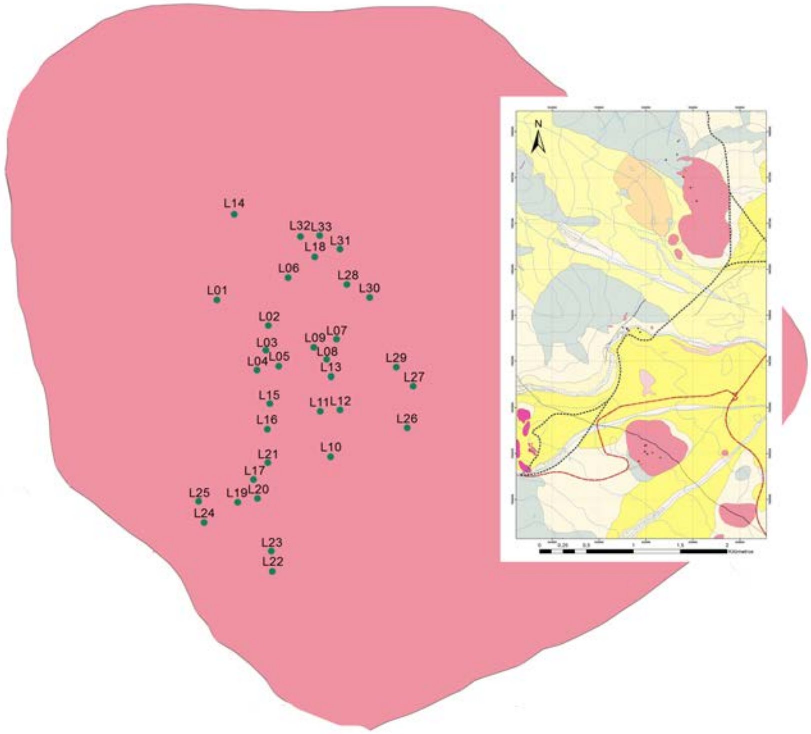

Figure 5. Production units identified during the intensive survey of the Ujina 8 site.
Unidades de producción identificadas durante las prospecciones intensivas del sitio Ujina 8.

Figure 6. At Ujina-8, 9, 10, 11 and 12, the smelting furnaces have a typical bench shape and are made with granodiorite blocks.
En Ujina-8, 9, 10, 11 y 12, los hornos de reducción tienen una forma de banco típica y están hechos con bloques de granodiorita.

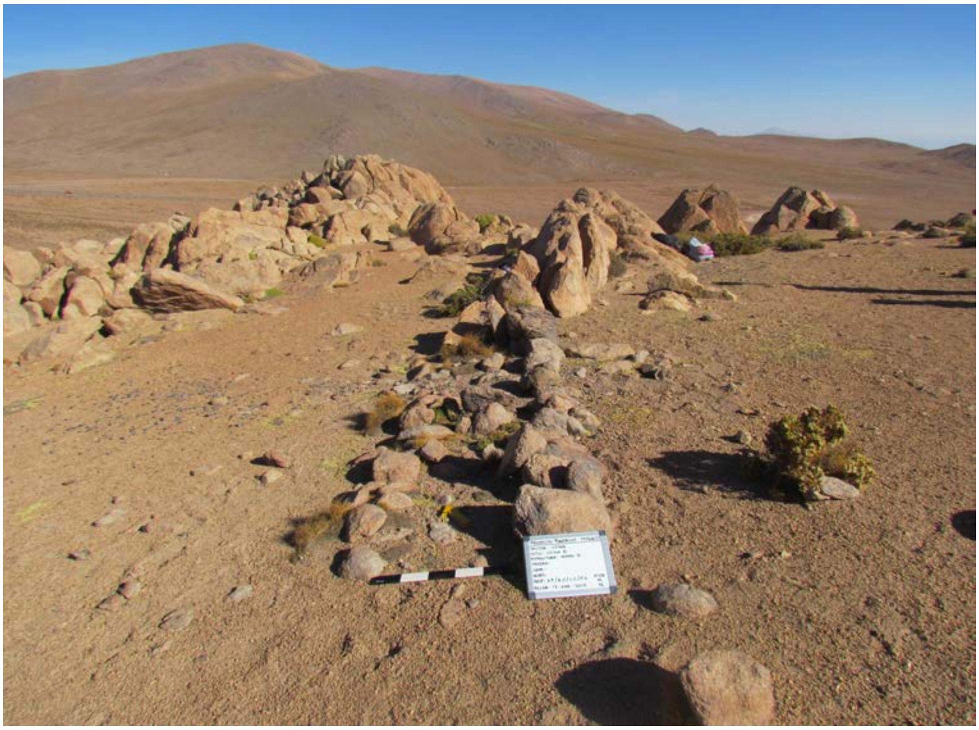

Figure 7. All the furnaces share common features, particularly a very long length (4 to 10 m), an orientation perpendicular to the dominant wind, and a back wall of a height not exceeding 1 m.

Todos los hornos comparten características comunes, particularmente una gran longitud (4 a 10 m), una orientación perpendicular al viento dominante y una pared posterior de una altura no superior a 1 m.

Figure 8. Each furnace was generally linked to a unique slag heap, which was located in close vicinity, but always a few meters away, in a place well protected from the wind.

Cada horno estaba generalmente unido a un único conjunto de escorias, que se encontraba muy cerca, pero siempre a pocos metros, en un lugar bien protegido del viento.

Study of Pre-Hispanic Copper Ores from Collahuasi

For this study, 40 rock fragments were collected from three archaeological sites—namely, *Collahuasi 37,* Ujina 8 and Ujina 10. The QEMSCAN® (Quantitative Evaluation of Materials by Scanning Electron Microscopy) analytical methodology was employed to measure the mineralogical variability of samples based on micrometer-scale geochemistry (Campos et al. 2015; Menzies et al. 2015). Modal mineralogy is shown graphically in Figure 9. The samples contain a mixture of Cu mineralization and gangue minerals (e.g. silicates). Copper mineralization ranges from 19% (Co37-m10-g) to 99% (UJ8-m6-a). Other mineralogy is variable, with some samples containing Fe-oxides (e.g. almost 20% in Co37-m13-b) and other samples containing abundant As-minerals (e.g. UJ8-m8-c, which has 36.58%). All samples have trace Ag-mineralogy levels above detection limits and ranging from 0.01% to 1.68 % (Co37-m11-b), but only five samples contain higher levels (>0.30%).

The results indicate that oxidized copper minerals -corresponding to malachite, chrysocolla and brochantite- were primarily used in the furnaces. That mineral association is present in the majority of the samples analyzed, and suggests that the ores selected come from the same source. Furthermore, the gangue in the samples is almost exclusively quartz. It is important to note that these results do not represent the percentage of mineralization of the source, and can only be used as a guide to link these ores with their exact origin in Collahuasi District. This is because the samples are hand selected and small and are thus biased towards mineralization and not comparable to source rocks at a larger scale. The most important impurities in the copper ores are As, Ag and Fe (Figure 10). As these impurities are present in the raw material, this would imply that they would also be present in the metallic copper produced from the reduction of those same copper ores.

The study of the pre-Hispanic copper slag and metallic copper from Collahuasi

The slags and the copper prills were examined and analyzed by optical microscopy, SEM-EDX and PIXE, at the Centre de Recherche et de Restauration des Musées de France (Paris, France). Copper slags from Co37, Ujina 8 and Ujina 10 were investigated. From their external features, they appear to have been very viscous: they are always small (centimetric size), of a globular shape and look like conglomerate slag (Bachmann 1980). This is confirmed in cross section by the presence of large copper prills still embedded in some samples. Copper metal could not be recovered without slag crushing, which probably occurred close to the furnaces, where slag heaps have been found. Ten slags were selected for metallographic examination (BF and DF Opt. Microscope); six of those slags were also examined in detail by SEM-EDX. Bulk analysis of the slag shows that they are rich in silica (47%±8), and relatively poor in iron (12%±7), which explains the high viscosity. Surprisingly, however, copper recovery was good, with loss usually below 20%. In our examination of the mineralogical structure of the slag samples, no unreacted silica was observed. Given also the presence of calcium (18%±8) and magnesium (3.2%±1.6), large crystals and needles of pyroxenes poor in iron formed from the matrix (diopside and wollastonite). In one case (UJ10 H1-3), the slag is totally calcium and magnesium free. Here again, almost no unreacted silica is observed. Tridymite and cristoballite crystallised instead of clinopyroxenes. Interestingly, this slag has the highest copper loss (ca. 30%) (Figure 11). Along with copper, silica, calcium and iron are the main constituents of the slags. This situation is very commonly encountered in the extractive metallurgy of copper. Here, most if not all of the initial charge reacted and reached the liquid state; the ternary phase diagram CaO-FeO-SiO2 can be used to approximate temperatures reached in the furnaces, and to explain the nature of the compounds that formed in the slag. Optimal slags are the ones located in the olivine domain (fayalite family, 2FeO.SiO2), since the melting point temperature of the olivines are the lowest of the diagram (eutectic valley around 1100°C), and these compounds are particularly fluid. Slags from Ujina and Collahuasi are not at all in the olivine field. The silica excess can easily be seen: most analyses are located in areas of high temperature silica forms (cristobalite, tridymite). Given the highlighted chemical system, the functioning temperature of the furnace reaches high values, at least 1200°C. The absence of unreacted minerals suggests that the smelting operation lasted for quite a long time.

Copper prills

Copper prills are also frequently encountered, either isolated or entrapped in slag. Metal analysis was performed by PIXE using the AGLAE facility (3 MeV tandem particle accelerator) (Dran et al. 2002). Results showed that the prills are composed of copper with a very typical As/Ag impurities association, sometimes with some iron and antimony. Thus, the composition of the metal produced in the bench-shape furnaces perfectly matches with the analytical results obtained for the copper ores, as mentioned above (Figure 12).

Fuel

The anthracological study of coal samples associated with Ujina (from Furnace 3 at Ujina 8) identified two

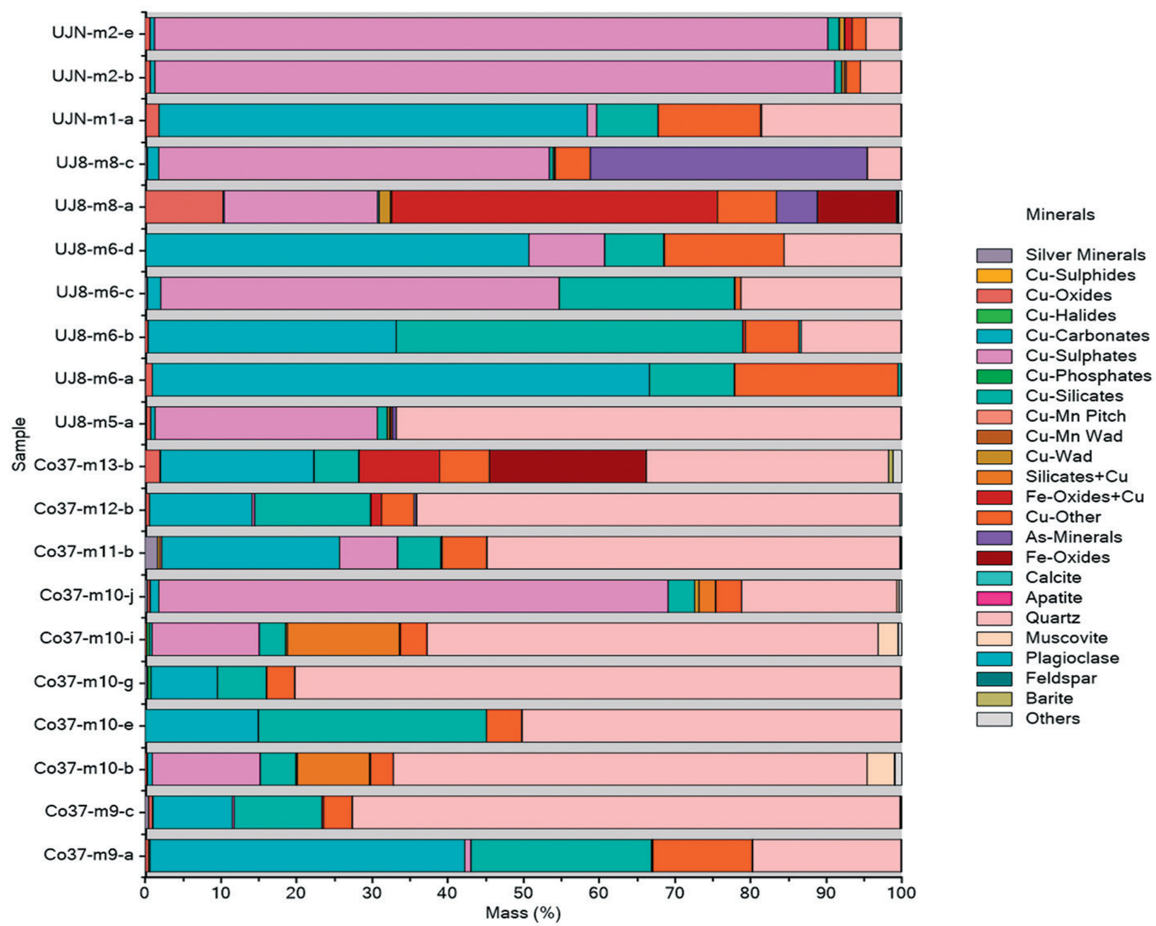

Figure 9. QEMSCAN analysis of the copper ore fragments indicate that oxidized copper minerals corresponding to malachite, chrysocolla and brochantite have been smelted in the furnaces.

Análisis QEMSCAN de los fragmentos minerales indican que los minerales de oxidados de cobre corresponden a malaquita, crisocola y brocantita fueron reducidos en hornos.

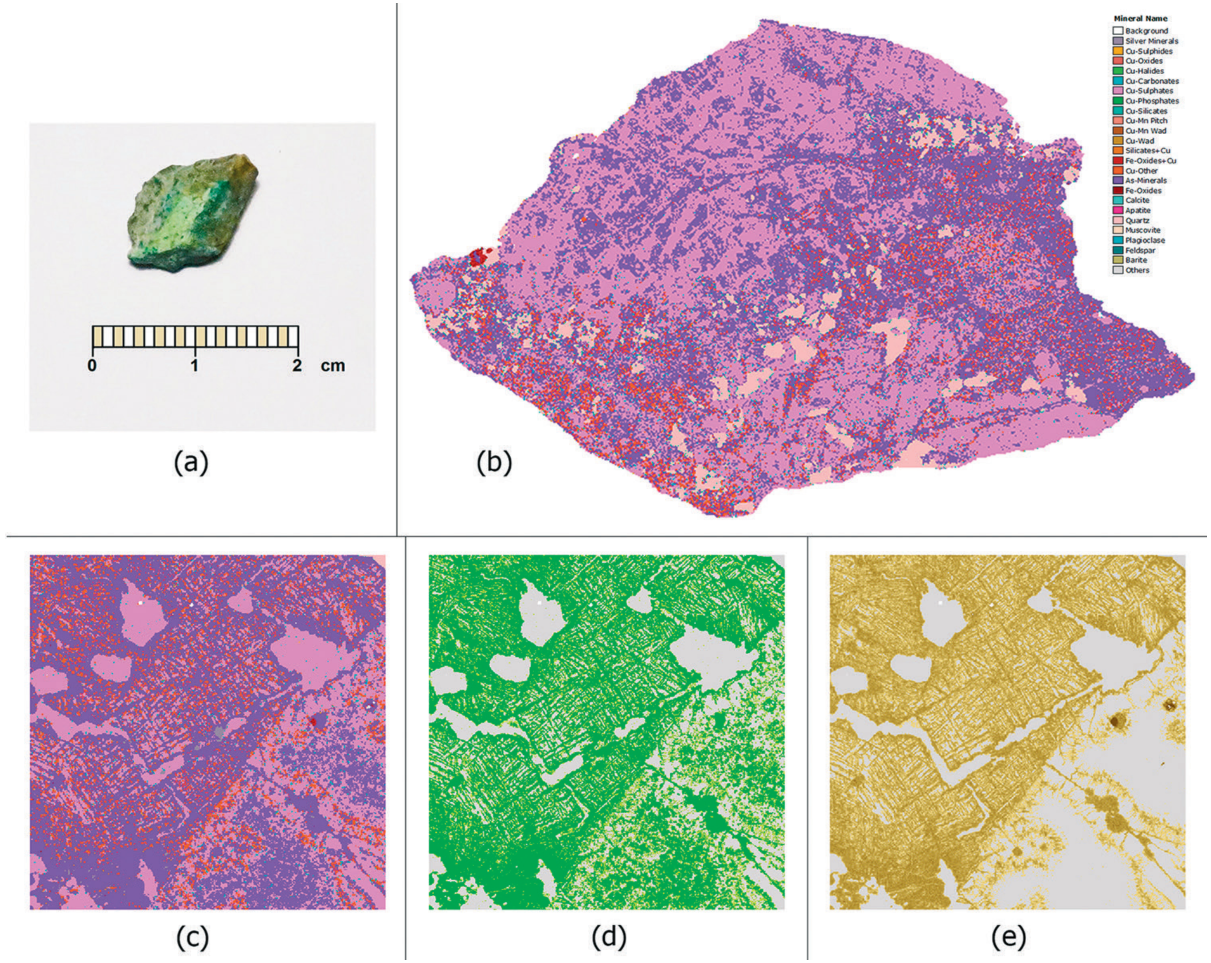

Figure 10. The most important impurities in the copper ores are As, Ag and Fe. QEMSCAN results for sample UJ8-m8-c has the highest levels of As-bearing minerals (36.58 %), predominantly incorporated into a variety of minerals as a minor or trace element, such as Fe-oxides; (a) Picture of sample UJ8-m8-c; (b) Mineral Map; (c) detailed mineral map (field of view is 1000 µm); (d) As element map; (e) Fe element map.

Las impurezas más importantes en las menas de cobre son As, Ag y Fe. Se muestran los resultados QEMSCAN para la muestra UJ8-m8-c que tiene los niveles más altos de minerales de As (36.58%), incorporado predominantemente en una variedad de minerales como elemento menor o traza, por ejemplo en los óxidos de Fe. (a) Imagen de la muestra UJ8-m8-c; (b) Mapa mineral de la muestra; (c) Mapa detallado (con aumento de 1000 µm); (d) Mapa para el elemento As; (e) Mapa para el elemento Fe.

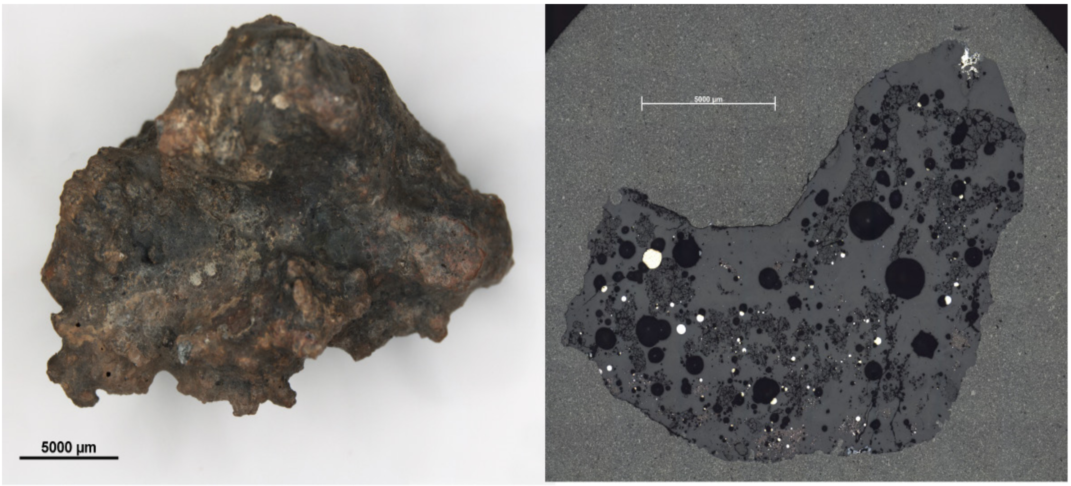

Figure 11. A tipical Collahuasi slag (globular shape and conglomerate minerals). Right: metallographic section of the corresponding slag, observation under Bright Field Optical Microscopy. The copper prills appear in white.

A tipical Collahuasi slag (globular shape and conglomerate minerals). Right: metallographic section of the corresponding slag, observation under Bright Field Optical Microscopy. The copper prills appear in white.

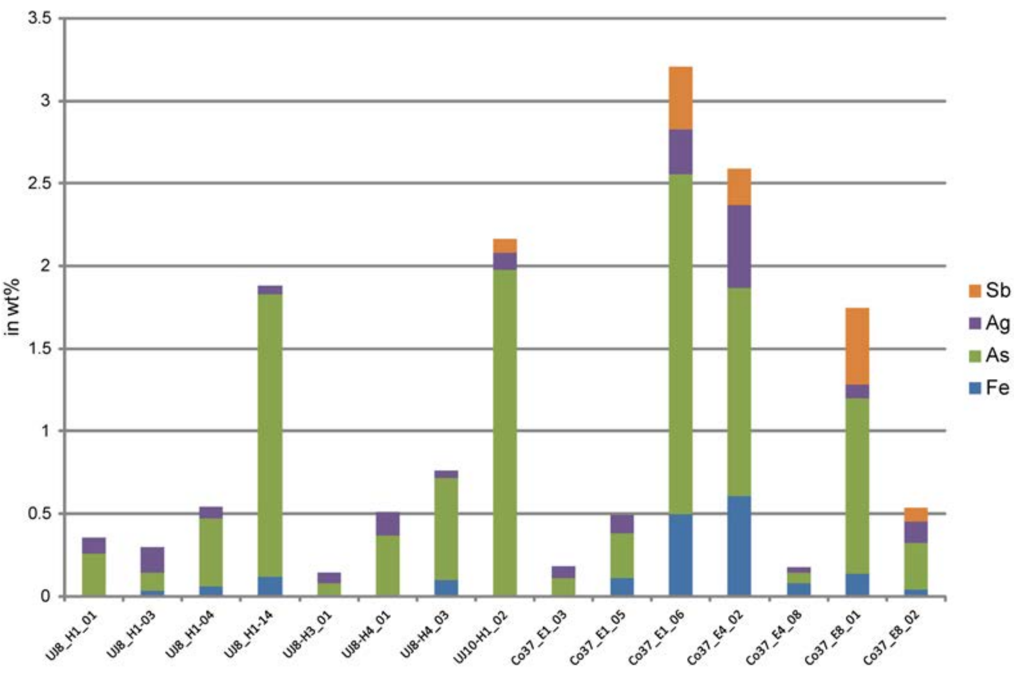

Figure 12. PIXE analysis of the copper prills, systematically detecting an As/Ag impurities association, sometimes with some iron and antimony.

Análisis PIXE de los prills de cobre, detectando sistemáticamente una asociación de impurezas As/Ag, a veces con algo de hierro y antimonio.

taxa that are available near the site -*Parastrephia* sp. (2) and *Polylepis* sp. (1). The three coal samples observed all displayed a high level of alteration, appearing as small areas with a shiny, vitrified appearance and, occasionally, a melted structure. The abundant presence of radial fissures on carbonized *Parastrephia* sp. (Figure 13) is typical of coal from this taxon previously observed in other anthracological studies (Joly 2008). Although the observation of a few coal samples is too meager to draw conclusions about the management and use of fuel employed in the furnaces of Ujina 10, the Collahuasi extractive metallurgy, it is however worth noting that both taxa mentioned herein are local species that have been commonly used as firewood from the pre-Hispanic period to the present day.

Wind: a crucial element for Collahuasi metallurgical operations

Wind was fundamental for the operation of the bench-shape smelting furnaces. In the Collahuasi District, local meteorological records show that strong winds from a very steady direction are present every day (Figure 14). Pre-Hispanic metallurgists took advantage of that airstream, constructing the smelting furnaces perpendicular to wind direction (Figure 15). In this way, the wind must be considered as a fundamental resource in the *chaîne opératoire* of the "metal collahuasi".

Discussion and Conclusions

The difficulty of clearly and systematically identifying Inca and LIP is a common problem in other mining districts, for several reasons. One of the main reasons is the particular nature of semi-permanent mining occupations of the LIP, which were impacted by occupations associated with Tawantisuyo that reshaped the prior architecture and as a result made it difficult to identify (1) the LIP, (2) the LIP in Inca times, and (3) the LIP with Inca presence. The particular nature of Co37 as a site situated in a zone with an extreme climate and without agricultural potential, means that occupations are less stratigraphically dense than those found, for example, at LIP sites in the northern and central Altiplano. We emphasize that, as a Collahuasi mining-metallurgical site, all food had to be brought in rather than produced in situ. While acknowledging the existence of pre-Inca occupation, prior investigations have emphasized the Inca character of the site and focused excavations especially in sectors with clearly Inca architecture. Precisely to respond to the transformations that occurred during the LIP as a result of the Inca presence at the Co37 and Ujina sites, we performed excavations in sectors D, E and F, which displayed no Inca architecture and had not been previously studied. Despite the initial goal of generating a diachronic breakdown, in all strata excavated in those sectors we observed the stratigraphic coexistence of ceramics from the LIP and Inca periods (Uribe 2017). The systematic association of LIP and Inca ceramics points precisely to that possible scenario, in which previously settled Tarapacá and Altiplano groups coexisted with the Inca presence, serving as the first major contingents to carry out mining-metallurgical labor, which they had already been performing in the district before that time. While it has been difficult, as mentioned, to find pristine LIP contexts, there is significant evidence that supports this hypothesis, in the form of several nearby LIP sites, the existence of LIP contemporary dates obtained for Co37, the presence of architecture in the local tradition, local ceramics, and the mining-metallurgical tradition of the region itself. Lastly, some dates associated with the furnaces of Ujina sector are also consistent with a LIP occupation (Table 1). Ujina has furnaces dated to the LIP, as well as other Inca ones. At the UJ10 site, furnace 3 yielded two dates: Cal AD 1281-1394 for layer 3 and an even earlier one Cal AD 1048-1217 for layer 3ª. For its part, furnace 1 yielded two dates-one of Cal AD 905-1025 (UJ10_H1_1_Ex) and the other of Cal AD 551-638 (UJ10_H1_3_N2). In relation to the dates of UJ8, all point to late moments of the LIP and also to Inca moments. It is interesting to see the dates of furnace 3: it is observed that the metallurgical operations lasted a few decades, making possible the idea that they were initiated during the LIP and that after the Inca domain the furnace would continue in use (UJ8_H3_B2ext_r2_N2: Cal AD 1276-1393 and UJ8_H3_B1_3_N3: Cal AD 1300-1412). The furnace 4 (UJ8_H4_2_N3: Cal AD 1328-1437) corresponds rather to a phase where the metallurgical site was already controlled by the Inca administration. In conclusion, both UJ8 and UJ10 presents LIP and Inca dates, which allows to propose a real diachronic production for at least two centuries. It is worth noting that at this stage of our investigation, we are not able to observe technological differences between the LIP and Inca furnaces. Instead, the Inca presence in the productive district and at the camp suggests that the Inca took advantage of the preexisting mining-metallurgical system and maintained the local technology, in line with the Inca strategy commonly observed in other mining districts in the south-central Andean area. In Collahuasi district, however, we observe a new expression of the spatial organization of production, which was modified to ensure adequate control of the production of semi-finished metals through the administrative architecture of Co37. This involved transforming a metallurgical camp with regional architecture by giving it the complementary function of a tambo in which activities

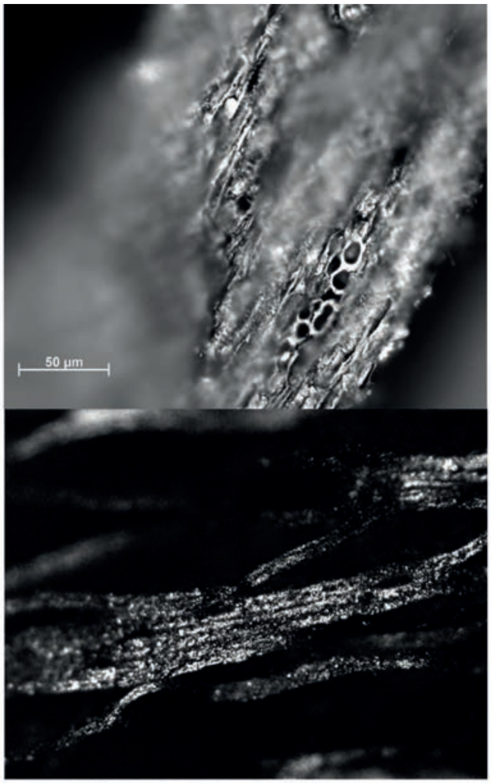

Figure 13. The anthracological study of coal samples of *Parastrephia* sp. associated with Ujina.

Estudio antracológico de muestras de carbón de Parastrephia *sp. asociadas a Ujina 10.*

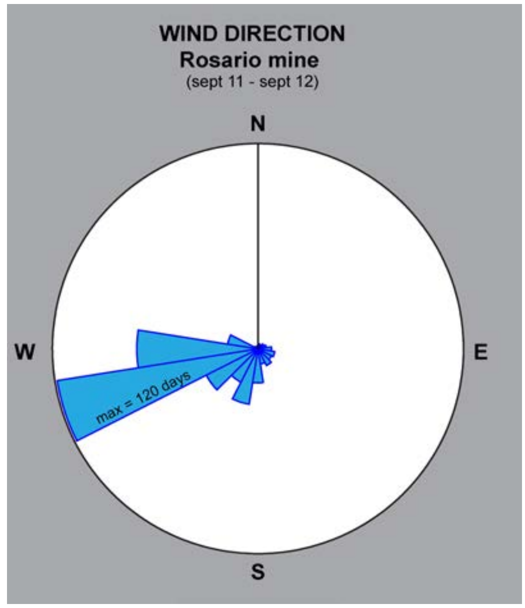

Figure 14. Local meteorological records show that strong winds from a very steady direction are present every day.

Los registros meteorológicos locales muestran que los vientos fuertes con una dirección muy constante están presentes todos los días.

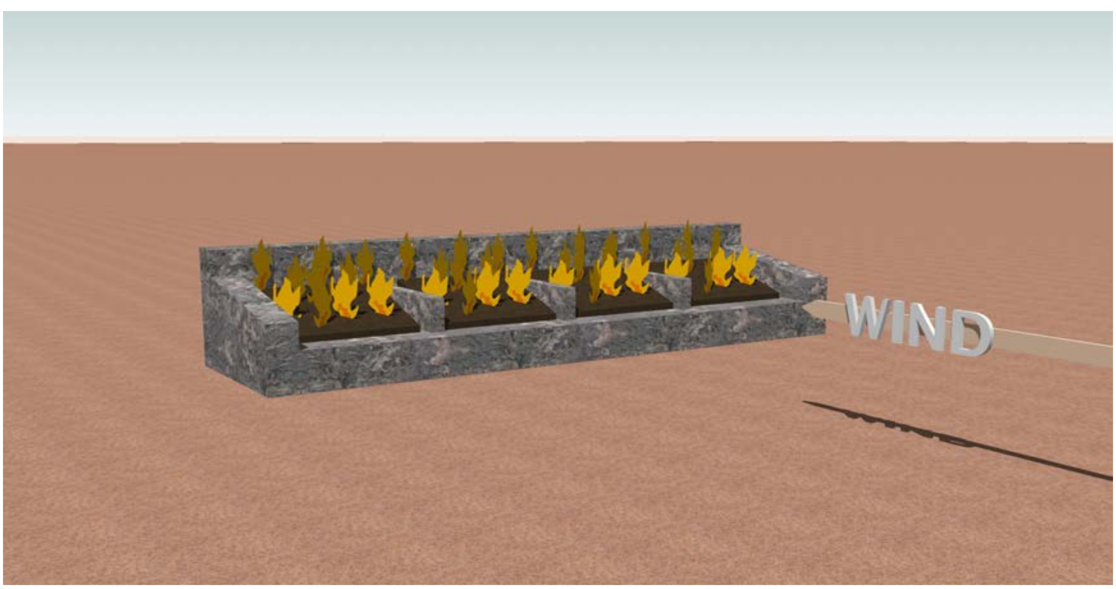

Figure 15. Reconstruction of the smelting furnaces perpendicular to wind direction.

Reconstrucción de los hornos de fundición perpendicular a la dirección del viento.

of political commensalism took place. It should be noted that we also identified a branch of the Inca Road running toward Co37 from the Inca platforms situated near Cerro Pabellón del Inca (Berenguer 2011) and connecting Co37 with the Inca Road near Miño district, where an ingot of metal with Collahuasi geochemical characteristics was also found in the Kallanka of Miño 2 (Salazar et al. 2013a).

Copper metallurgical production has been practiced in the Collahuasi District since the beginning of the Late Intermediate Period (LIP) through the use of technology based on furnaces with stone backing apparently uncommon in Northern *Chile*. In that mining district, the Inca took advantage of the pre-existing mining-metallurgical system and maintained the use of the local technology. The study of metallurgical production sites indicates that the Incas made no significant changes in metallurgical technology. What they did change was the way production was organized. In other words, the spatial organization of production was changed to ensure proper control of the half-finished metal during the process. A possible important change was that ore selection and “winning” of the metallurgical slag was not only performed alongside the furnaces as was apparently done during the LIP, but also at the Co37 Inca camp itself. During the Inca Period, copper would also have been extracted at the *Rosario* mine although there is no record of this owing to the intensive modern-day operations there—and reduced at the UJ-8, UJ-9 and UJ-10 sites. Co37 was a metallurgists’ camp, even though the site also served as a waystation (*tambo*) where, judging by the architectural and material record, official gatherings were also held. The predominant ceramic materials found at the Co37 site suggest that the main contingents that occupied this metallurgists’ camp came from Tarapacá Region. Nevertheless, other groups -whether from the Tarapacá Altiplano, or even (miners?) from Atacama region- may have participated in the system as well. Here, there would have been an accumulation of both unprocessed ore extracted from the mine and post-reduction slag. During the Inca period, this production system was coordinated regionally via the Inca Road and the empire’s administrative centers (Miño, for example), which would have allowed the semi-finished products to circulate. The metal would have left the camp as a semi-finished product (prills and/or ingots) destined for other consumer regions. We hope that future analyses of the elemental composition of the finished objects will allow us to identify those circuits of distribution and redistribution of Collahuasi copper. It will be of first importance to compare the results with the Inca district of Tarapacá Viejo (Zori 2011).

The incorporation of new technologies into the study of pre-Hispanic archaeological ore samples from the Collahuasi District has generated very detailed information. Specifically, automated mineralogy (QEMSCAN®) has yielded detailed Cu-mineralogy results for raw ore samples found in association with copper smelting furnaces at a pre-Hispanic mining-metallurgical site. Our study also identified the presence and mineralogical association of impurities such as As, Ag and Fe. Lastly, the description of the above-mentioned samples provides a baseline for comparison with future studies of other archaeological sites and/or possible local or regional Cu ore sources.

We have identified one of the most important metallurgical sites in Northern Chile and a kind of smelting furnace previously unreported in the literature, a furnace whose operation and technology were unknown to date. Research on mining and on metallurgy in Northern Chile has heretofore been conducted separately. Indeed, there is a disconnect between the investigation of mining production systems and that of metallurgical production systems. This paper has sought to reconnect those systems into a single mining-metallurgical system through a study focused on the Late Intermediate and Late periods in the Collahuasi Mining District of the southern Tarapacá Altiplano, thereby expanding our knowledge of the variability and transformations that have occurred in Andean metallurgy.

Table 1. Calibred radiocarbon dating of Ujina 8 and Ujina 10 (calibration 2 sigmas with OxCal program 4.3).
Tabla 1. Fechados radiocarbónicos calibrados de Ujina 8 and Ujina 10 (calibración 2 sigmas con programa OxCal 4.3).

LabSample	site	structure	level	BP	error	from (cal.)	to (cal.)	%	sample
D-AMS 009914	Ujina 8	Furnace	UJ8_H4_2_N3	528	22	1328	1437	95.4%	charcoal
D-AMS 022761	Ujina 8	Furnace	UJ8_H3_B1_3_N3	591	26	1300	1412	95.4%	charcoal
D-AMS 022762	Ujina 8	Furnace	UJ8_H3_B2ext_r2_N2	662	30	1276	1393	95.4%	charcoal
D-AMS 009915	Ujina 10	Furnace	UJ10_H3_3_N1	648	26	1281	1394	95.4%	charcoal
D-AMS 009916	Ujina 10	Furnace	UJ10_H3_3A_N2	883	20	1048	1217	95.4%	charcoal
D-AMS 009917	Ujina 10	Furnace	UJ10_H1_3_N2	1475	22	551	638	95.4%	charcoal
D-AMS 009918	Ujina 10	Furnace	UJ10_H1_1_Ex	1050	22	905	1025	95.4%	charcoal

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