EMPA and EDXA Analysis of Slag from the Multicomponent Site of Pirque Alto, Bolivia

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ABSTRACT

In June 2007 the UW-L Bolivian Archaeological Field School uncovered two features consisting of rings of standing stones at the multicomponent agricultural site of Pirque Alto near Cochabomba, Bolivia. These features contain a form of unidentified slag within the ring, indicating that the features served as reduction furnaces. This paper demonstrates, by means of electron microprobe analysis, the composition of the slag sample as well as the nature and purpose of the forge features, and their probable date. EMPA indicates that the slag itself is the result of copper smelting occurring at very high temperatures indicating that the features served as the bases of huayrachina furnaces. This paper utilizes information from past research on the site of Pirque Alto as well as ethnographic accounts of huayrachina use to imply a Middle Horizon (C.E. 500-1000) date to the smelting activities of Pirque Alto, as well as technological influence from the site of Tiwanaku.

INTRODUCTION

Figure 1:Map of Bolivia with the site of Pirque Alto marked (McAndrews and Rivera 2007)

The site of Pirque Alto is located roughly 15 kilometers west of the city of Cochabamba, in the Department of Cochabamba, Bolivia (figure 1). It sits 2km from the modern village of Pirque. The site lies at the confluence of three major corridors: the Rio Pukina valley leads to the northeast and the Central Valley, the Rio Tapacari channel leads Northwest towards the Titicaca basin, and a southwesterly corridor leading toward Oruro. This strategic location at a major crossroads of natural Andean pathways indicates that the site was of importance to any group hoping to control or profit from trade between the major regions of pre-Hispanic settlement. It is obvious, then, why a population of sedentary farmers would occupy the site throughout the Common Era.

Archaeological work at the site began in June 2005 with a 100% surface collection conducted by Drs. Timothy L. McAndrews and Claudia Rivera and members of the University of Wisconsin La Crosse 2005 Summer Field School. This revealed ceramic components from the Formative Period through the Late Horizon, indicating that Pirque Alto was inhabited throughout Andean prehistory (McAndrews and Rivera 2007).

During the summer of 2007 Drs. McAndrews and Rivera returned to the site with the UW-L 2007 summer field school to begin excavations. Units were chosen based on the areas of highest ceramic concentration for each period indicated in the surface collection. Limited excavations were conducted within 5 excavation blocks. This paper focuses on the excavation conducted in Excavation Block IV, primarily the features marked as Feature 3 and Feature 6 (McAndrews 2007). These features contained a very fine soil matrix as well as a dense concentration of artifacts, including a form of slag. Ceramic evidence obtained during excavation places the reduction feature in either the Late Formative (1 C.E.-C.E. 500) or Middle Horizon (C.E. 500-1000).

Figure 2:Excavation Block IV showing features 3 (center) and 6 (right) (McAndrews 2007)

The purpose of this paper is to investigate the composition of the slag material found at Pirque Alto. To this purpose the slag material was subjected to electron microprobe analysis (EMPA). Based upon the results of this study, and with the help of several geology and chemistry specialists at University of Oklahoma, the original chemical makeup of the ore reduced at Pirque Alto was determined. This determination provided clues to the nature, date, and purpose of features 3 and 6 (Figure 2), as well as potential influence of the Tiwanaku polity at Pirque Alto. This analysis also provides the first reductive metallurgy study done in the Cochabamba area.

BACKGROUND

Cultural Context

The Andean region of South America was and remains a highly culturally complex area. The vertical nature of the terrain creates multiple self-contained ecological niches within a small horizontal area. This ecological diversity is mirrored by the diversity of cultural groups within the region. It is therefore even more fascinating that this region would be the site of one of the few primary state formations in human history. The history of the Andean region is often defined by the presence or absence of a pan-Andean art and representative style in prehistory, and by the obvious presence or absence of an administrative empire during Inca and colonial times.

There are two major theories about when the first major shift toward a pan-regional art style occurred. These two theories are not mutually exclusive and hinge primarily upon what area is being studied. When Max Uhle defined the sequence of Andean civilization in the early parts of the 20^{th} century he was basing his chronology primarily upon expeditions to modern Peru (Uhle, 1903). The standard system has a long archaic period of pre-agricultural peoples which was then overtaken by the Initial Period of early agriculturalists.

The timing of this transition varies depending on the environment, even to the level of individual river valleys, but to generalize it can be said that the Pre-Ceramic to Initial Period transition was in full swing by one thousand B.C.E. (Mosley 1992). Following this initial period was the civilization of Chavin de Hauntar, which represented the first pan-Andean art style. This marks the beginning of the Early Horizion which stretched in the highlands of Peru from 500 B.C.E. until roughly C.E. 0. This period of relative stability and incorporation was succeeded by the Early Intermediate Period in which the pan-regional style of the Early Horizon was abandoned and the various cultural groups within the various Andean regions again expressed their individual identities rather than their affiliation to a larger coroporate body in their material culture.

This period was followed by the Middle Horizon, which lasted from roughly C.E. 500-1000. This five hundred years mark the first examples of state level societies "native" to some parts of the Andes, specifically the Lake Titicaca basin. Within the region of Northern Bolivia known as the Altiplano during the Middle Horizon a settlement known as Tiwanaku arose. While at first merely a small agricultural community, during the Early Intermediate the city of Tiwanaku would grow to incoroporate a massive public and ceremonial core based upon megalithic construction and terraced mounds, generally containing sunken courts (Mosley 1992).

By the latter parts of the Early Intermediate and throughout the Middle Horizon, the city of Tiwanaku represented the core of a region spanning state-level society, which controlled regions stretching from modern day Cochabamba in Bolivia to the northern Atacama in Chile. The nature of this control is not entirely understood, however Llama caravans transported various goods to the capital and returned with the products of distinctive raised field agriculture as well as ceramics and other items manufacture in the Tiwanaku art style (Mosely 1992). It is also known that the Tiwanaku civilization created colonies, perhaps the best documented in the region known as Moquegua. This region supported several Tiwanaku outposts and was transformed over the course of the

Early Intermediate and Middle Horizon into a province of the Tiwanaku state (Goldstein 1989).

The other dating technique common to prehistory of the Andean Region is primarily functionalist in nature and demonstrates that outside the boundaries of modern Peru there is little evidence of a pan-regional synthesis in art and technology prior to the Middle Horizon. This system therefore dates the entirety of agriculture Andean prehistory prior to the Middle Horizon into a long Formative era, with Lower, Middle and Upper designations. In effect, the Upper Formative and Early Intermediate are generally equivalent.

Following the end of the Middle Horizon in C.E 1000 the Andean region was again segmented into several cultural regions. However, the dawn of the Inca Empire in C.E. 1500 would change the course of Andean civilization by incorporating the entire region into a single administrative unit, with its center at Cuzco, until the time of Spanish contact.

History of Archaeometallurgical Analysis

The primary focus of archaeometallurgical analysis prior to the 1960s focused on the composition and classification of finished products (Alunni 2006). It was through finished artifacts that the technology employed in the actual construction of artifacts was inferred (Menzel 1952). There are two primary downsides to this focus on finished articles: first, that much of the artifactual corpus available to us dates from the Incan imperial period, or Late Horizon (CE 1200-1532). secondly, and more importantly to this thesis, is that the analysis of finished objects by definition excludes the arts of extractive metallurgy. As will be detailed below, the function and execution of extractive and productive metallurgy are entirely separate and even today performed by two or more separate groups of highly specialized analysts.

Through inference from finished products it is possible to learn that the Inca had access to several extremely well developed techniques for the working, joining, and extraction of gold, silver and copper (Menzel 1952). However, the descriptions of extractive metallurgy, even in colonial South America, are extremely limited and unspecific. Described are the use of “huayrachinas” which is directly translated from the Quechua language as “a place that wind blows through” (Mills and Van Buren 2005). The word “huayrachina” is shortened to “Huayra” in many publications and the term seems to be used interchangeably by those doing archaeometallurgy in the Andes (Alunni 2006, Mills and Van Buren 2005, Lechtman 1996, 1991). The use of the Huayra seems to have reached the Cochabamba region during either the Late Formative or the Middle Horizon and to have spread outward with the Tiwanaku cultural expansion (Menzel 1952). Due to the focus in the literature on either the ethnographically present Huayra technology or on the artistically stunning worked objects the analysis of smelting techniques in the Cochabamba region are extremely sparse. In fact, it has been suggested that no smelting or extractive metallurgy of any form occurred in the Andes previous to the Middle Horizon (Menzel 1952). During the Early Horizon easily available deposits of placer gold and native silver were utilized for the production of Chavin metalwork, and the decline of metalwork during the Early Intermediate by is explained the depletion of these easily attainable deposits and the inability of the local people to exploit the deeper deposits precious ore indicated by the placer deposits themselves (Menzel 1952).

There is a tradition that Inka metalworkers encountered and utilized highly efficient smelting technology generations later and there have been detailed studies of post-contact smelting technology and excavation techniques in Bolivia (Alunni 2006, Mills and Van Buren 2005). However, no detailed chronological sequence of pre contact extractive metallurgy for the Cochabamba region has been performed. More broadly, the area encompassing modern day Bolivia, south of Tiwanaku, has been poorly studied with regards to pre-contact metallurgy.

The area where most Andean archaeometallurgical research has been done to date is the Northern Atacama Desert in modern Chile and the surrounding regions, particularly southern Peru. The most well documented pre-contact smelting site in the Andean region is the Middle Horizon site of Batan Grande in Southern Peru. Excavations of over 50 pear shaped bowl-furnace structures with lung powered blow tubes for temperature regulation revealed that the site was utilized for metallurgical purposes from C.E. 900-1532 (Shimada and Merkel 1991). The structures utilized were not huayrachina furnaces, and the slag viscosity achieved was not optimal necessitating the crushing of smelted material to extract the metallic copper.

At the site of Ramaditas in the Guatacondo valley of the Atacama desert in Northern Chile extractive metallurgy was carried out on a periodic basis during the Late Formative Period, around 500 B.C.E. (Graffam et al. 1994). The extremely low slag viscosities achieved and the highly efficient nature of the smelting carried out points to the possible utilization of huayrachina furnace technology at Ramaditas. However, the furnaces themselves have been destroyed over time, and their exact original form cannot be reconstructed.

Description of huayrachina furnace

The huayrachina or Huayra wind-blown furnace was a short structure constructed of cobble and grit tempered clay set atop a large pedestal of rock at the top of a hill or other wind-swept place (Mills and Van Buren 2005, Alunni 2006). Huayrachinas of the colonial era were generally slightly less then a meter in height, about 30cm wide at their base and roughly 50cm wide at their top (figure 3). They were oval in construction and possessed multiple holes on the two larger sides directly across from one another to allow wind to penetrate the huayrachina during smelting (Capoche 1959[1585], Acosta 1954[1590]). Ethnographic information indicates that the huayrachina was traditionally constructed with two large ceramic “doors” on the two larger sides to allow for the charging of ore and fuel, as well as a ceramic spout at one of the smaller sides which generally drained into a ceramic bowl producing “lacey” metal (Mills and Van Buren 2005). This type of finished product would be a distinctive indicator of Hauyrachina use were it found archaeologically. Unfortunately it is extremely unlikely that smelted but un-worked metal would be found due to the tendency of many people in Andean prehistory to recycle metal goods.

Figure 3: ethnographic huayrachinas and owner (Peel 1893)

Both portable and stationary versions of the huayrachina existed at the time of contact (Peterson, 1970). This indicates that some were relatively lightweight and that they were likely owned individually even before the influence of Inca and Spanish conquest. Peterson also describes several other forms of furnace, including one constructed of loose rocks formed together without mortar, with holes for air to pass through. This description is likely based upon either the misinterpretation of firsthand huayrachina accounts or the outright lies of the Spanish occupation, as it is not only unlikely to have survived operation in a harsh wind environment without mortar but would also represent a technological backslide compared to the accepted method of smelting several centuries before Spanish conquest (Alunni 2006, Menzel 1952).

This problem, specifically that the only known written references to pre-huayrachina smelting techniques are catalogued by sources either so misinformed or so racist as to contribute the invention of the huayrachina itself to a Spaniard, leave any suggestion of accuracy entirely suspect (Mills and Van Buren 2005). It therefore falls to the archaeologist to produce the account of pre-contact smelting technology.

Relevant Chemistry and Physics of Pyrometallurgy

The first process discovered in the art of forging was likely annealing, or the process of heating a metal to make it softer, more ductile, and easier to work. This process was vital for the formation of the distinctive sheet copper artifacts found in association with Chavin sites (Menzel 1952). This requires significantly less heat than that necessary to actually melt the metal, which is the primary goal of reductive metallurgy. As such, this process, and several closely related processes such as alloy soldering can be utilized and even perfected long before the acquisition of sufficient heat-capture technology to make reductive metallurgy possible.

The vast majority of metal on earth exists as chemically bonded ore material. To win pure metal from this ore material it is necessary to provide the bonded element with a more tempting partner. To illustrate, the most basic process for reducing copper ore to metallic copper follows the formula.

$$CuCO_3 + CO >> Cu + 2CO_2$$

This equation shows how, by means of heat, the reduction of copper carbonate can be achieved through the creation of a carbon monoxide rich atmosphere (Alunni 2006). Similar equations can be worked out for the reduction of gold, iron, and other common metals.

Unfortunately for the utilization of copper as an early medium for tools, the vast majority of copper deposits in the world are combinations of copper with sulfur, not oxygen (Alunni 2006). Indeed, the majority of ores on earth, with the notable exception of tin, are found primarily as sulfides. Unfortunately for early smelters, sulfide ore charged directly into a Huayra would not have resulted in the production of pure metal. The reason for this is that within the anoxic atmosphere surrounding a charge of ore within a reduction furnace, the sulfur does not have sufficient oxygen to bind with and therefore cannot be extracted from the ore. This problem can be solved by a method known as “roasting” where a piece of sulfide ore is cooked over an open fire, however there is a much simpler and more efficient method of reducing sulfides: cosmelting (Alunni 2006, Lechtman 1991).

The process of cosmelting is extremely simple and involves charging both an oxide and a sulfide ore into the same furnace, and treating the amalgamation as if it were an oxide ore. The chemical reaction that follows can be typified by this equation (Alunni 2006).

$$8CuCO_3 + Cu_3AsS_4 >> Cu,As + 4SO_2 + 8CO_2$$

In this equation, the oxide of copper (in this case copper carbonate) combines with a sulfide of copper (in this case enargite) in the heat of a reduction furnace to produce sulfur dioxide and carbon dioxide, as well as pure metallic copper and pure metallic arsenic. In this specific case the real-world result would be a copper-arsenic hybrid typical of the highland Andes (Lechtman 1996). This reaction allows the sulfur within the sulfide to reduce the oxygen within the oxide and produces metallic copper from materials otherwise difficult to work. The majority of ore in the Andes, and in the world, is a mix of oxides and sulfides (Alunni 2006). This would have made cosmelting not only the logical choice, but a likely occurrence whether intentional or not.

Electron Microprobe Analysis

Electron microprobe analysis (EMPA) is a relatively new technique, developed in the 1950s as a new method for analyzing the small-scale structure and composition of materials. The technique has been used to analyze the physical structure and chemical composition of material culture. Specifically, it has found use in the realm of archaeometallurgy for its ability to not only identify the elemental composition of a artifact sample, but to show the arrangement thereof in two dimensions (Fraikor et al. 1971, Merkel and Wang 2001).

EMPA utilizes a focused beam of electrons produced from an electron emitter (generally a tungsten filament cathode) which are accelerated to extremely high energy through the use of a positively charged anode with a very small hole in the center. The electrons are accelerated towards the anode, and allowed to pass through the hole. They then enter a series of magnetic lenses which function on the electron beam much like the optical lenses of a microscope act on light, focusing and directing the beam towards the desired area (Figure 4). The beam of electrons then impacts the material, affecting an area generally no larger than 3 cubic micrometers. In a gross oversimplification of the process, this beam of electrons allows us to “see” into the substructure of the sample within the tightly delineated area of the electron probe (MNEMPL 2007).

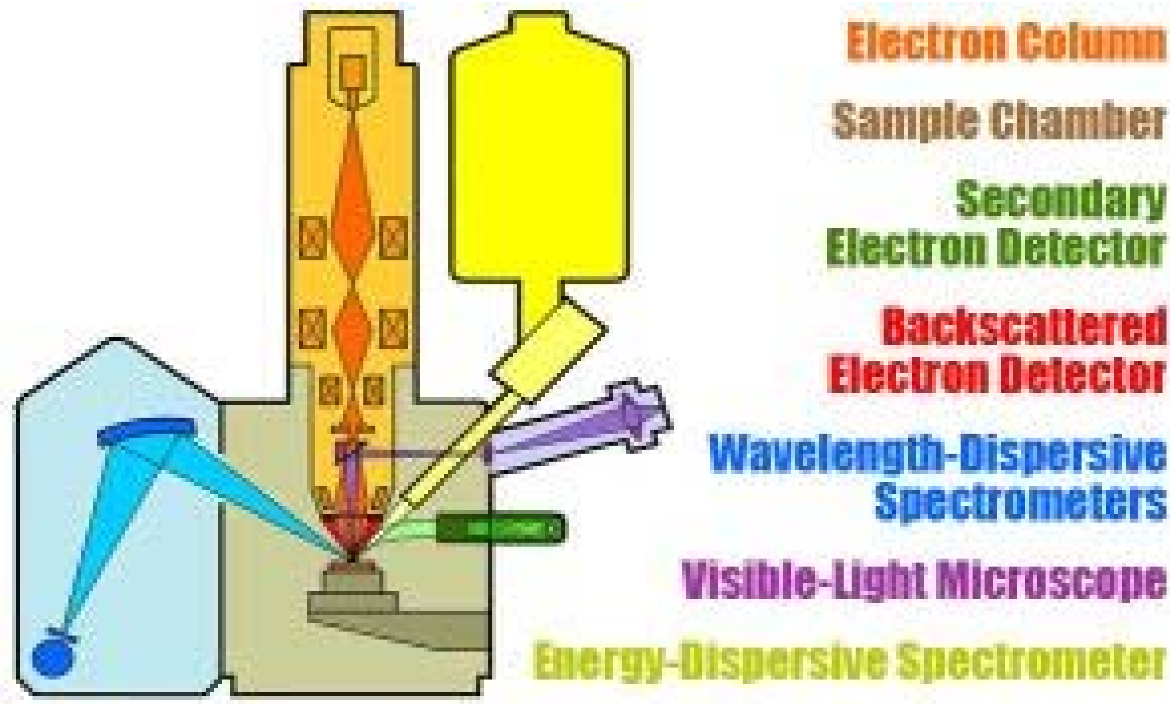

Figure 4:An Electron Microprobe Analyzer, courtesy of the University of Minnesota Electron Micro-Probe Laboratory.

This fact reveals the major weakness of EMPA, which is that only a very small section of an artifact can be analyzed at any one time. Care must be chosen to select a representative portion of a sample, and samples themselves are generally less than a two cubic centimeters.

Energy Dispersive X-Ray Spectrography

The capabilities of the Electron Microprobe allow it to function as a catalyst for Energy Dispersive X-Ray Spectrography, or EDXA. In EDXA, the highly energized beam of electrons from the microprobe is focused upon a small section of the sample. This high energy beam impacting the sample causes the electrons of its constituent atoms to become excited, emitting energy. This energy, in the form of x-rays, is of a distinctive wavelength unique to each type of atom. These x-rays can be collected and analyzed by use of an x-ray spectrometer, and the element associated with any given x-ray can be determined. This allows the electron microprobe to record not only optical information from a sample but also its chemical makeup.

METHODOLOGY

Excavation

Excavations at Pirque Alto were conducted within 5 blocks. Excavation blocks I-V were chosen based upon the concentrations of ceramics from differing time periods as determined by the initial 100% surface collection of Pirque Alto by McAndrews and Rivera (McAndrews and Rivera 2007). Excavations proceeded utilizing arbitrary 10cm levels. Excavation block IV was located near the western edge of the site and was $7m^2$ in size, sterile soil was reached at a depth of 1.5m. It was chosen due to a high concentration of Middle Horizon artifacts, as well as its location near the base of a steep slope. This location indicated the possibility for deep stratified cultural deposits. This is exactly what was discovered within Excavation Block IV. Several features were also found, features 3, 4 (a gray ash lens), 4d (an infant human burial), and 6 were all located within the block.

Features 3 and 6 consisted of several vertical stone slabs with a maximum height of roughly .5 meters. The slabs were arranged in a circular pattern with a diameter of roughly .6 meters. It is likely that the structures stood taller during use, due to the broken and uneven nature of tops of the feature stones. Features 3 and 6 contained a very fine soil matrix with a dense concentration of artifacts, including human bone fragments. The association between the bone fragments and the features is not clear as they were found near the base of the stones (McAndrews, 2007). This fine soil matrix also contained the unidentified slag material analyzed in this paper. A sample of this slag material was collected from feature 3 and brought to the United States for analysis by Dr. McAndrews.

Electron Microprobe Analysis

EMPA was conducted on the sample at the University of Oklahoma by Bernard Schreiver and Drs. London and Morgan. A small subsection of the slag sample was prepared for analysis by thick section and embedded within a 1" pvc ring using a two component epoxy. The section to be analyzed was ground flat and placed within the ring. Once the epoxy set, the surface to be analyzed was polished with a series of successively finer grit films and diamond slurries, with the final grit being a .25 micron diamond slurry on a cloth pad. Once polished, the thick section was sonically cleansed to remove impurities and carbon coated to make the sample electrically conductive and to ground the sample.

Once prepared, microphotographs were taken of the sample to determine possible areas of interest, as well as for orientation during EMPA. These microphotographs as well as the image results of the EMPA were downloaded as Tiff files and both saved and printed to be used as reference for further analysis.

EDXA was performed on selected areas of the sample. These results were both uploaded as visual Tiff files as well as statistically analyzed and produced as graphs and tables. All three types of results were both saved to hard disk and printed.

RESULTS

Electron Microprobe Results

The electron microprobe analysis indicates that the slag sample is indeed the byproduct of ore reduction. The sample consists of four mineral phases (Figure 5). Phase one consists of circular "droplets" of metal consisting primarily of copper with small amounts of iron. This phase is represented by white on the false-color photograph below. Phase two, the next lightest phase, consists primarily of iron oxide crystals in two forms. The larger less skeletal crystals contain measurable aluminum and titanium, whereas the small more skeletal crystals do not. Phase three, the second darkest and most prominent phase, consists of Iron Silicate, with measurable amounts of manganese, calcium and magnesium. This phase is remarkably homogenous throughout the sample regardless of texture or size. Its chemical composition is similar to olivine. Phase four, the darkest phase consists of a glassy, disordered silicate phase. It is an artificial composition, not naturally occurring, although it is closest to an alkaline glass. The two "skin" phases were formed by the outer edges of the sample cooling faster than the inner portions (preceding analysis, Figures 5-8, and Tables 1,2 courtesy of Bernard Schreiver, personal communication 2008).

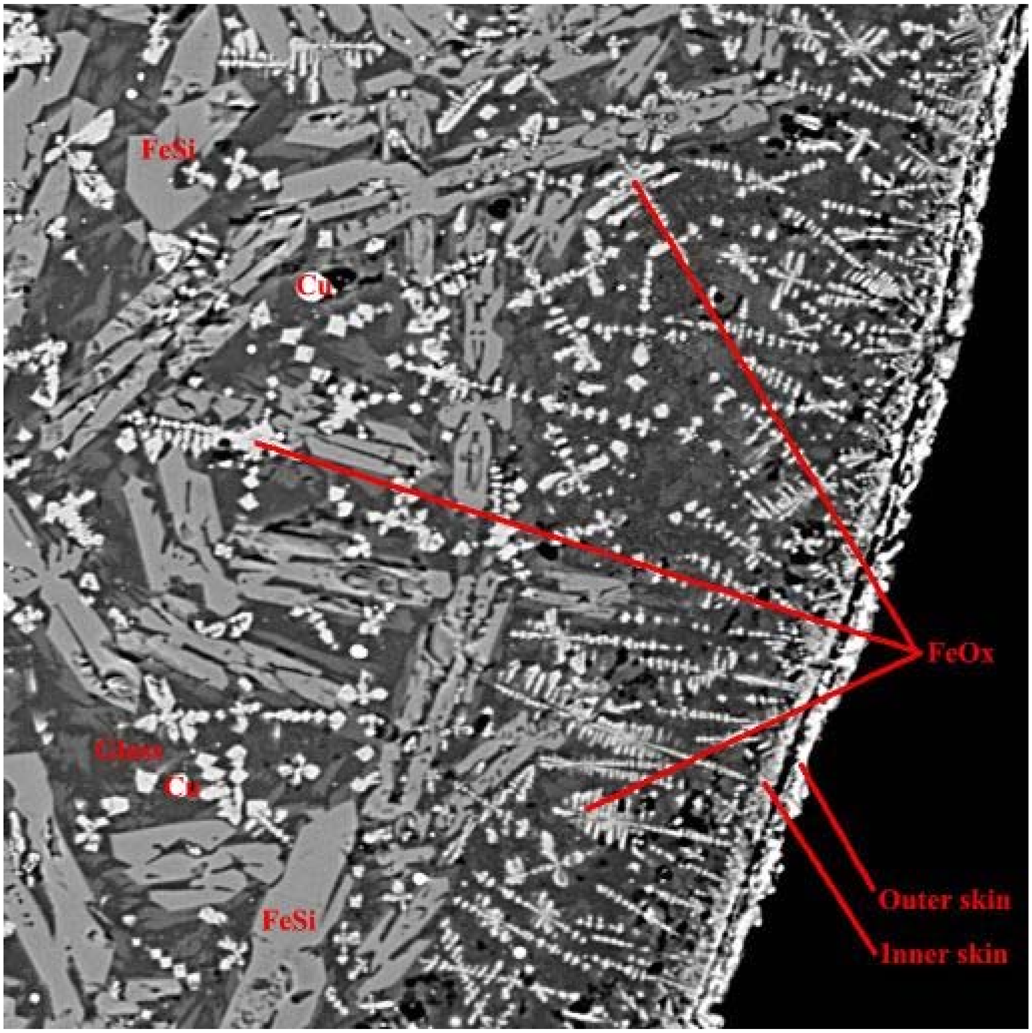

Figure 5:Area 3 of the slag sample, with the chemical composition of phases 1-4 marked

Also of note in the sample was the presence of large cavities (Figure 6). These empty locations are evidence that the sample was at one point a molten liquid. They were likely caused by gas bubbles being trapped within the sample during its molten phase, a key aspect of reduction.

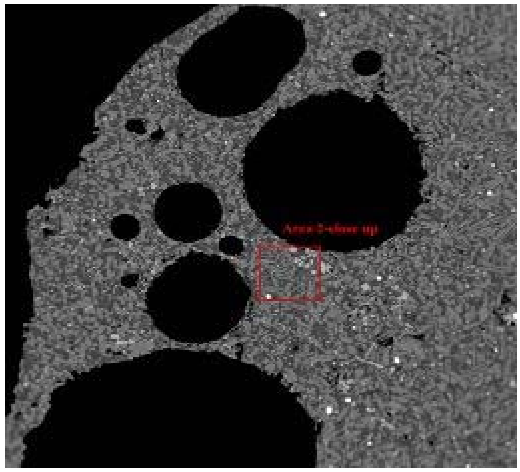

Figure 6:Sample under low magnification, showing ‘bubble’ cavities

EDXA Results

Elemental composition data were gathered utilizing EDXA on a randomly selected area of the sample. The chemicals useful for separating the four phases were: Ca=Calcium, Cu=copper, Fe=iron, K=potassium, Mg=magnesium, O=oxygen, P=phosphorus, and Si=silica. The two tables and graphs below contain this composition data for phases 1 (Figure 7, Table 1) and 3 (Figure 8, Table 2), the two most relevant to this paper.

Phase 1

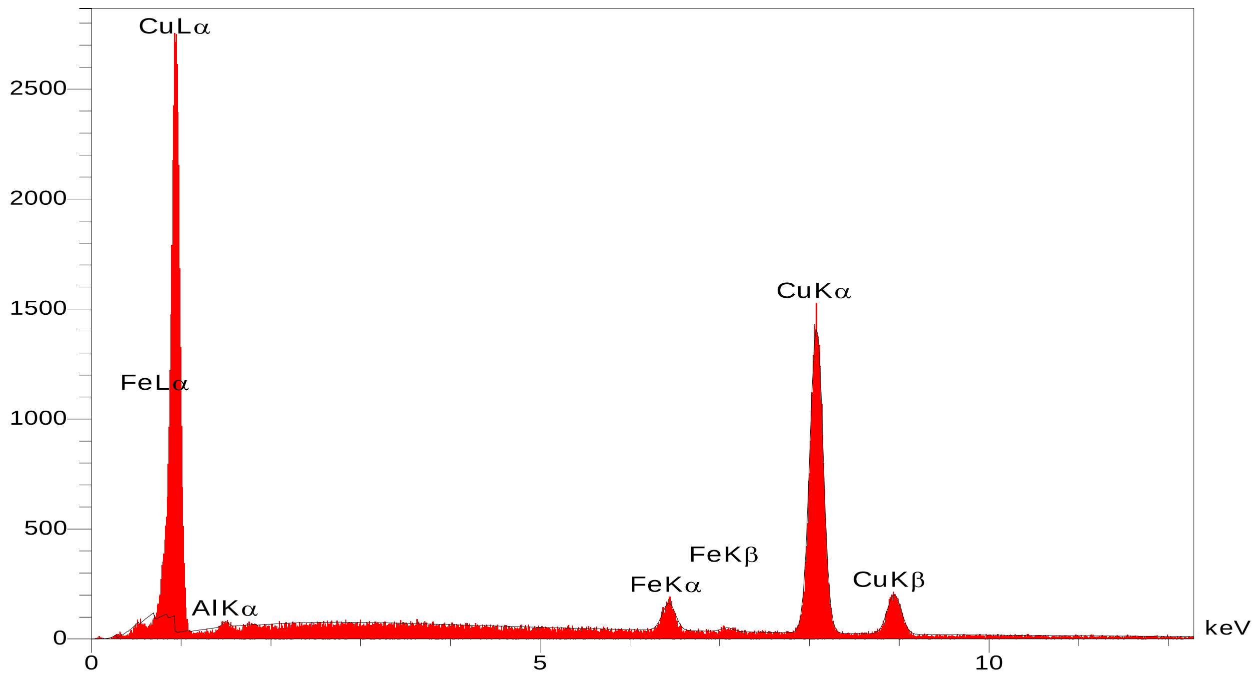

Figure 7:EDXA graph showing primarily copper composition of Phase 1

Elt	Line	Int	W%	A%
Al	Ka	6.3	0.40	0.93
Fe	Ka	73.3	3.96	4.45
Cu	Ka	840.2	95.64	94.61
			100.00	100.00

Table 1:The chemical composition of Phase 1

Phase 3

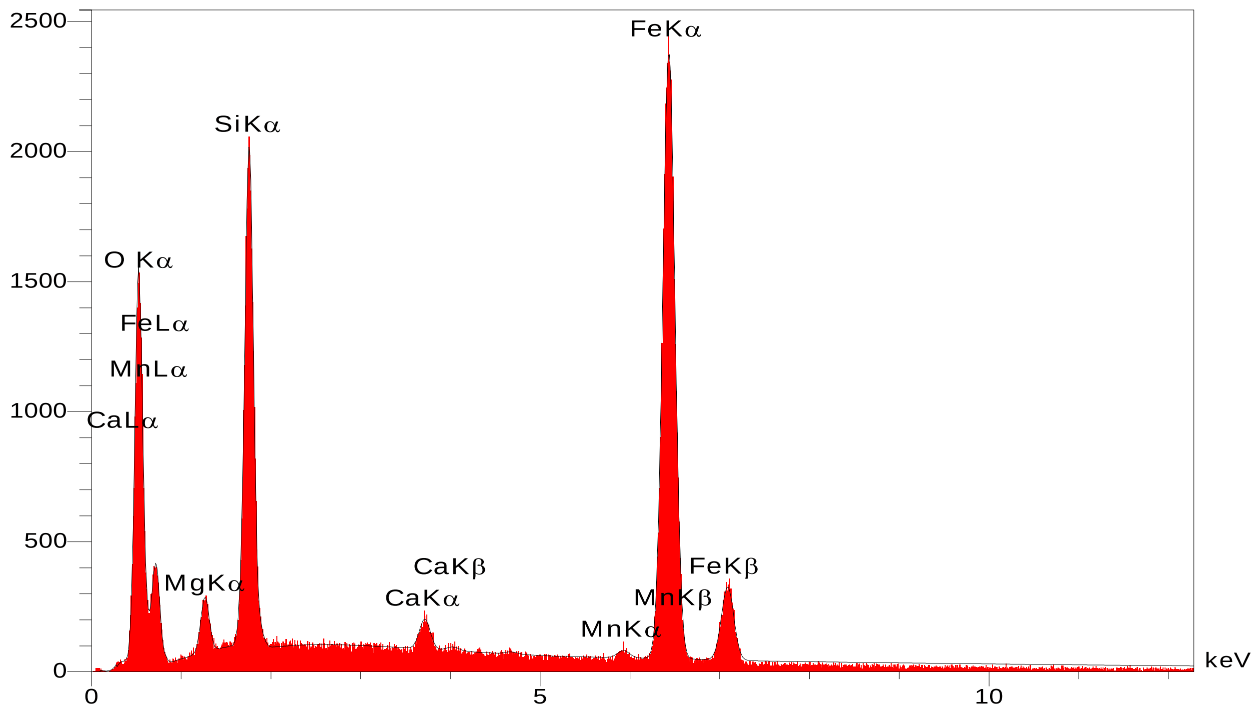

Figure 8:Graph showing the Iron Silicate composition of Phase 3

Elt	Line	Int	W%	A%	Formula	Ox%	Cat#
O			31.96	56.77		0.00	0.00
Mg	Ka	42.6	2.53	2.95	MgO	4.19	0.21
Si	Ka	381.3	13.38	13.54	SiO2	28.62	0.95
Ca	Ka	28.5	1.01	0.72	CaO	1.42	0.05
Mn	Ka	7.6	0.51	0.26	MnO	0.66	0.02
Fe	Ka	652.5	50.62	25.76	FeO	65.12	1.81
			100.00	100.00		100.00	3.05

Table 2:Showing the chemical composition of Phase 3

The chemical composition of phase 3 indicates that it is likely a byproduct of high temperature smelting. The chemical composition resembling olivine indicates that the sample was fired as very high temperatures, likely reaching above 1150 C (Bernard Schreiver, personal communication 2008). The presence of Ca is possibly the result of an intentional addition to expedite the slag formation process. The presence of iron, oxygen and silicate compounds indicates the formation of a common type of slag in copper reduction known as fayalite. The formation process of fayalite is outlined below (Alunni 2006).

$$Fe_2O_3 + CO >> FeO + CO_2$$

$$2FeO + SiO_2 >> 2FeOSiO_2$$

Feyalite

The presence of calcium in the sample indicates either that a different slag process was underway, or that the calcium is a chance addition based upon where the ore material was acquired. Furthermore, the presence of Olivine indicates that the oxygen fugacity, or ability of oxygen to interact with the charged ore, was very low during the smelting procedure. This would have required a large amount of control during the smelting process to ensure that too much oxygen did not enter the reaction. The burning of easily acquirable charcoal with camelid dung or grasses used to ignite the fire would have produced sufficient CO and CO_2 effectively limit the oxygen consumption of the reduction reaction (Mills and Van Buren 2005).

The chemical composition of phase 1 is likely the remnant of copper prills, or droplets, trapped within the slag during the smelting process. This presence of pure metallic copper is an indication that the reduction of metallic copper from copper ore was the primary aim of the smelting occurring at feature 3 and 6 of Pirque Alto. Although the slag contains large amounts of iron, there is no metallic iron preserved by the slag. This high concentration of iron and copper also indicates that the chemical composition of the base ore was likely chalcopyrite or a derivative thereof. This copper and iron bearing ore is found within discontinuous veins throughout the Andes and likely provided a large quantity of the copper ore utilized during the prehistory of the region.

The extraction of metallic copper implies a use for this material. This means that either there were specialized smiths on site who were producing copper tools and ornaments from the smelted stock, or that the site of Pirque Alto was performing a vital step in the process of metal artifact production by acquiring and refining pure metal and its residents transporting the metallic copper to other sites where smiths could make use of it. This type of economic differentiation is characteristic of the Incan and Spanish Colonial Mita system, and it is possible that something similar was already taking place during the Middle Horizon.

CONCLUSIONS

The first and most important conclusion that can be reached from the analysis performed is that the slag found at Pirque Alto represents the intentional reduction of chalcopyrite into metallic copper and slag. This process achieved temperatures of 1150C and was almost certainly carried out utilizing either the huayrachina furnace technology prominent during the Middle Horizon, or an earlier precursor if the features date from the Upper Formative. The presence of Ca and Olivine within the slag indicates that the smelters at Pirque Alto were either knowledgeable of the properties of slag formation and utilizing that knowledge to expedite their tasks or that they were fortunate enough to acquire their ore samples from easy to smelt sources. Trace element analysis and source-survey data will be necessary to definitively prove either hypothesis and carbon dating is necessary to confirm a date for features 3 and 6.

The chemical makeup of the original ore was very likely chalcopyrite, as indicated by the presence of Cu, and Fe in the slag. This mineral is common throughout the Andes and in Bolivia with major sources occurring at all historic and modern silver and copper mines.

I propose that the utilization of efficient smelting technology at Pirque Alto is directly related to the florescence of the Tiwanaku Polity in the South-Central Andes circa C.E. 600. The site of Pirque Alto is strongly associated with this cultural shift (McAndrews and Rivera 2007, McAndrews 2007). Although it is possible that the construction and utilization of huayrachina furnaces was not restricted to Chile during the late formative period, it is far more likely that the rise of Tiwanaku and the associated upsurge in metal production are correlated with, although not necessarily causal to, the utilization of huayrachina technology at the site of Pirque Alto. It is also possible that the Llama caravans utilized by the Tiwanaku polity encountered and transferred the knowledge of huayrachina construction and utilization from their possible Atacama origin at sites like Ramaditas first to the central Tiwanaku core and then throughout the colonial regions. The presence of several huayrachinas on site would indicate that there was at least a trade in technology with the ritual center and at most a distinct specialist population originating from Tiwanaku on site at this time.

Further research is necessary to provide source and site data for the ore utilized at Pirque Alto. Carbon 14 dating could also confirm the dates of features 3 and 6, as well as the slag material itself. It would also prove fruitful to analyze more samples of the slag found on site to determine if multiple different types of metals were being reduced, It is possible that not only metallic copper but other precious metals were produced at Pirque Alto. Further excavation and analysis are also necessarily to definitively prove the link between huayrachina technology in the Cochabamba region and the influence of the Tiwanaku polity. Finally, experimental archaeology could provide detailed information about the capabilities and limitations of huayrachina technology.

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