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Tracing firing technology through clay properties in Cuzco, Peru

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ABSTRACT

The purpose of this study was to identify changes in firing practices that occurred during a timeframe that saw the introduction of European kiln technology to the Andes (AD 900–1800). Pottery from an excavated context at the archaeological site of Aqnapampa in the southern highlands of Peru was examined for changes in paste recipes that adapted local materials to increased firing temperatures indicative of evolving firing technologies. Sherds (60) and fragments refired to 890 °C from 12 stratigraphic levels were compared by style, surface treatment, paste color, and vitrification structures (ESEM). Four technological phases of the Cuzco pottery sequence emerged and were used to evaluate the trajectory of a single decorative style (Killke). Previously thought to have been produced in pre-Inca times and curated into later periods, the Killke sherds presented evidence that the style was produced using technologies introduced in the Inca and Spanish Colonial Period.

1. Introduction

The expansion of the Inca Empire and its subsequent replacement by the Spanish colonial endeavor left its mark on the material culture and practices of the Late Horizon and Early Spanish Colonial Period in Peru. Both culture contact situations introduced new, distinctive artifact styles and technologies to the far corners of the Andean world that would serve to mark time in the archaeological record. The 16th century arrival of the Spanish in the New World introduced a pottery style easily distinguishable from those manufactured by existing indigenous technologies. The new group included glazed pottery from Europe (majolica), Chinese porcelain via the Philippines, and glazed pottery produced elsewhere in the New World using newly introduced kiln technologies and paste recipes. While glazed pottery was in demand by early Spanish colonists in Peru (AD 1532–1570), it did not appear in quantity in indigenous contexts of the southern highlands of Peru until possibly as late as AD 1600 (Chatfield, 2007; Jamieson, 2000; Smith, 1991; Van Buren, 1997). Meanwhile, indigenous people continued to manufacture many of the prehispanic pottery styles throughout the Spanish Colonial Period, making it difficult to use style to differentiate indigenous Spanish Colonial Period sites/phases from those of earlier times. Determining whether or not indigenous Andeans were conservative in adopting new pottery methods is the topic under consideration.

Based largely on style, the regional pottery sequence of the Inca heartland is the primary means for dating archaeological contexts, although it is weakened by stylistic continuity. Integrating a technological dimension to the ceramic sequence of this dynamic period of culture contact allows for a more nuanced reading of the regional chronology. In particular, refining the late prehistoric sequence can inform the highly contested question of Inca origins (Bauer, 1992, 2004; Bauer and Covey, 2002; Covey, 2003, 2006, 2008; Hiltunen and McEwan, 2004; McEwan, 2006; McEwan et al., 1995, 2002, 2008) and bring to light the early colonial period in the archaeological record. Key to this study is the understanding that paste recipes crafted by experienced potters in prehispanic times would have required reformulation to adapt to the new firing technologies introduced by the Spanish. In the process, the "melting point" of the clay fabrics originally formulated for firing in open bonfires would have increased to compensate for the higher temperatures sustained in kiln firings.

This study tracks changes in the original firing temperatures and clay maturation temperatures through time in a collection of sherds excavated from multiple stratigraphic levels of the same unit. The data set was gathered from 60 bowl/plate sherds spanning the Late Intermediate – Spanish Colonial Periods (AD 900–ca. 1800) at the site of Aqnapampa, near Cuzco, in the southern highlands of Peru (Fig. 1). All sherds, which were from vessels of the same size and function, were evaluated with regard to decorative style, surface

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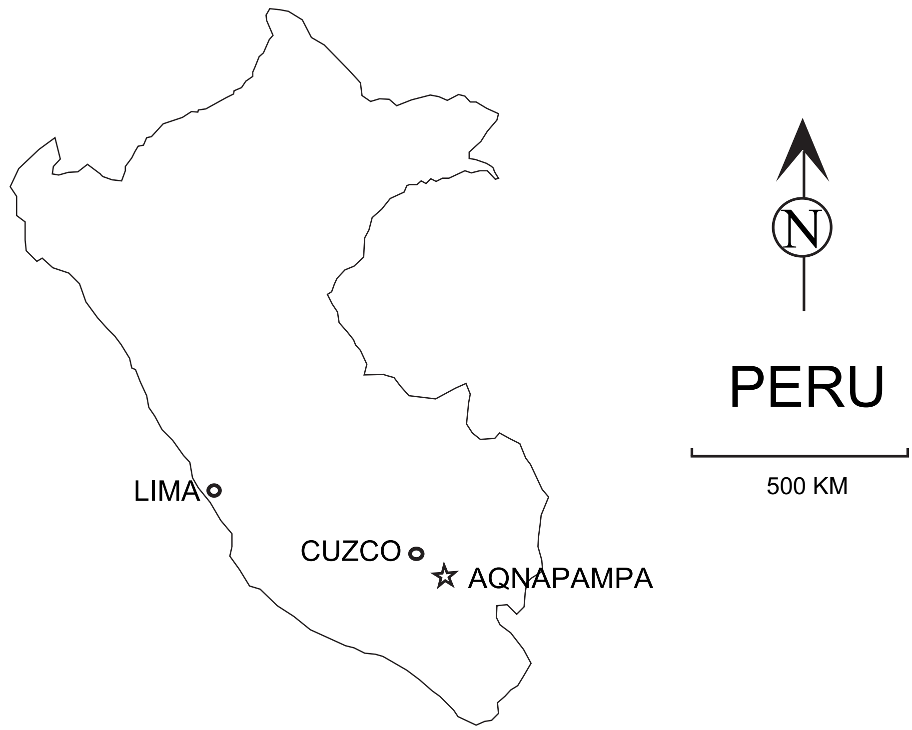

Fig. 1. Map of Peru and Cuzco region.

treatment, paste color (before and after refiring), and degree of vitrification (before and after refiring). Imaging of the vitrification structures was performed using environmental scanning electron microscopy (ESEM) on the original clay bodies at ×800 magnification and these were compared to the vitrification stages achieved by refiring samples of each sherd to a temperature of 890 °C sustained for 30 min in an oxidizing atmosphere. Comparing microstructures provided information on the extent of vitrification and pore structures, which permitted the inference of original firing and maturation temperatures (relative to 890 °C) and, thus, the potential of each clay formulation to have withstood a kiln firing event.

2. Firing methods

In order to assess the introduction of European firing techniques, it is necessary to examine the fundamental issues faced by specialists using bonfire vs. kiln methods. Open firing techniques, such as bonfires, and closed procedures, such as kilns, differ in the maximum temperature that can be sustained, the speed with which high temperatures can be achieved, and the proximity of fuel to the pots (Rice, 1987: 157; Tite, 1999: 188). In a table comparing ethnographic data on open firings and kiln firings, Rye (1981: 102–103) demonstrated that major differences exist between these two techniques. The maximum temperature of an open firing is achieved in most cases within 12 min of the start and in all cases within 50 min. Also, the cooling process is shorter for open than it is for closed firings, allowing for removal of the pots within minutes to hours of the maximum temperature, rather than days. Since high temperatures cannot be sustained in open bonfires, open technologies rarely result in overfired pots (Rice, 1987: 106–107). Finally, in open techniques, fuel is placed on and among the pots being fired, creating pockets of oxidizing, reducing, and neutral atmospheres within the same firing episode. The atmosphere fluctuates as gases are released from both the clay and burning fuel, while gusts of wind create uneven combustion. The result is a varied batch of pottery due to lack of control over the principal elements.

While the vast majority of pre-Colonial Andean pottery was fired using open methods, there is evidence of attempts to develop closed firing technologies on the north coast of Peru. Formative Period ovens at Batán Grande, which are the Andean structures most similar to European kilns, were small (<1.5 m × 0.50 m), peanut shaped, underground pockets containing an open firebox on one end and a ventilation chimney on the other. Pots were loaded from the top and covered with large sherds for insulation. Firing experiments using the prehistoric structures rigged with thermocouples estimated a longer firing schedule than traditional open firings. Peak temperature was achieved 60 min after the start and maintained for approximately 30 min. The cooling period was approximately 1.5 h long. The peak temperatures, varying in different places within the oven, reached 700–800 °C, which is not different from those attained in open firings (Shimada et al., 1994, 2003; Wagner et al., 1999). Like the bonfire techniques, fuel was packed among the pots, and also in a firebox at one end, which allowed fuel to be added during the event, extending the process. Fuel packed around and between the pots favored a reducing atmosphere, while closed sidewalls provided insulation that sustained heat and channeled the draft of the insulated pit in one direction. Research on firing temperatures of pottery from Inca production workshops (Tambo Real and La Viña, in La Leche Valley) indicates higher temperatures that are usually associated with insulated bonfires or simple kilns (Hayashida et al., 2003). Using Mössbauer spectroscopy, researchers determined that cambered-rim cooking jars and flared-rim jars (also known as arybalos) fired at the coastal production center reached temperatures 850–950 °C and in one case as high as 1000 °C. As the area was part of the Mochica–Chimu potting tradition and is located at low elevation, it is unclear whether or not the products of this coast Inca workshop are technologically the same as those found in highland production centers or even in Cuzco. For example, it is known that the vessels from these coastal workshops were formed using vertical press molds typical of the area, while in the highlands these vessels are made using the coil method (Hayashida et al., 2003: 154; Lunt, 1988). Likewise, the firing method could have been a continuation of coastal techniques for firing larger vessels or cook pots.

In addition to archaeological examples of insulated firing methods found on the north coast, ethnographic examples of insulated bonfires have been documented in the southern highlands of Peru and Bolivia (Sillar, 2000a, b). In the majority of cases, indigenous potters opt for firing without permanent structures using several approaches to heat retention/modulation, such as shallow pits, windbreaks, cover sherds, corrugated iron sheets, burnt chunks of earth from previous firings, and layered fuel, to name a few. However, the most efficient insulator is dung, which burns steadily and retains its shape and insulative properties in its ashen state. These factors combine to create a pocket of heat in dung firings that, in my experience of firing pots with sheep dung, can maintain a temperature of 750 °C for 38 min (700 °C for 66 min with a peak of 792 °C), although others have reached temperatures as high as 865 °C (Nicklin, 1981). Due to the fact that lead glazes are fired in one town using insulated bonfires, Sillar surmised the firing temperatures to be "not much below 900 °C" (Sillar, 2000a: 47). The type of dung used as fuel also impacts firing temperatures (Winterhalder et al., 1974), as llama dung has a higher heat value than cow or sheep dung. With regards to insulating the firing process, cow dung may have the advantage due to its large size of each output, the benefits of which would not have become apparent until cows were introduced to the Peru after the 1530s. Until then, camelid dung would have been used in its natural form (pellets) or possibly reshaped. Potters today using the insulated bonfire method place unfired pots on a bed of pellets (sheep, llama) and cap the pile of pots with a layer of cow chips before layering on grass, dirt clods, or other fuels (Sillar, 2000a, b).

Closed firing technologies provide the means for increasing the maximum temperature, sustaining the heat for a longer time, and controlling the firing atmosphere. Kilns are usually permanent structures with insulating walls and at least two chambers, one acting as a fire box and another keeping the pots separate from the fuel, thus giving the potter better control over the oxidizing or reducing atmosphere. The insulated walls pool heat within the structure while protecting the firing process from moisture and gusts of wind. The separate firebox permits the addition of fuel throughout the firing process without burying the pots in the ash of spent fuel. Kilns have been used for firing various types of high-fire clays (such as stonewares and porcelains), attaining maximum temperatures tailored to the specific clay formulation, but kilns that are employed for firing earthenware clays typically achieve temperatures in the range of 750–950 °C (Tite, 1999). Unlike open bonfires, closed firing techniques ramp up the temperature slowly, attaining the maximum temperatures 3.5–11.5 h after ignition (Rye, 1981: 102–103). The long periods of sustained heat are accomplished by continually adding fuel to heat the kiln structure. The cooling periods last from 1 to 4 days in some cases (Rye, 1981).

Despite broad differences between open and closed firing regimes, procedures for firing pottery have been found to fall along a continuum of increasing insulation between these two extremes. Compilations of ethnographic firings document a wide range of insulated bonfires as well as rudimentary kiln methods that address temperatures and ramp rates in addition to structure, fuel, and issues of time (Gosselain, 1992; Livingstone Smith, 2001). Such studies agree that the maximum temperature achieved by a firing is not enough to infer prehistoric firing methods from sherds because too much variation exists within each firing. Temperatures fluctuate between pots based on their placement within the firing arrangement and within a single pot. Determining the firing procedure is best accomplished through ramping rates and the soak time (Gosselain, 1992). Additionally, through comparison of firing sequence data from present day potters in Africa and Asia, it was determined that similar soak times and temperatures can be achieved using insulated firings and simple kilns (Livingstone Smith, 2001). However, ramping rates themselves do not remain constant throughout a firing event, particularly as higher temperatures are achieved. For example, increasing from 50 °C to 150 °C can occur in 1 min using an open or closed method while the increase from 800 °C to 900 °C might take 30 min or more. Furthermore, none of the ethnographic firing events documented significant soak times (30 min or more) above 900 °C, most likely because none of the firings dealt with glazed pottery that would require higher temperatures. It could be argued that the kilns were fired to meet the requirements of the pots and the raw materials, rather than to showcase the full potentials of the firing structures in terms of soak times and temperatures. The firing schedules of open and closed firing technologies demand different performance characteristics of the clay pastes, such as the optimum firing temperature (maturation temperature). A paste recipe designed for an open firing technique that is fired in a kiln using a glazing schedule will emerge overfired. Nevertheless, most ethnographic fieldwork offers little information about the clays involved or their properties. The following discussion suggests a method for retrieving relative maturation temperatures from archaeological sherds through the study of vitrification stages.

3. Microstructure and maturation temperature

Time, temperature, and atmosphere are variables that potters manipulate to adapt firing conditions to specific raw materials used in their paste formulations. A shift in one variable without a compensatory shift in the other two will yield different results in the final fired product. Closed firing techniques have the advantage of conferring greater control over these variables than a potter would have over an open bonfire technique. The factors of soaking time and temperature and ramping speed permit mineral and chemical alterations to take place in the clay that result in the desired properties of the final product. Within a clay body, a thermal reaction sequence occurs in a predictable order and, if the same clay recipe is compared, at predictable temperatures (Rice, 1987: 102–103). The formulation of a clay body, consisting of the original clay(s) and temper (natural or added), combines uniquely to yield a fabric with an optimal firing range, known to studio potters as the maturation temperature, which is the final point before the clay begins to melt (Brody, 1980). Altering the paste formulation can increase or decrease the maturation temperature and thus impact the timing and temperature at which the steps of the thermal reaction sequence occur, including the vitrification stages. Impurities in the clay or materials intentionally added by the potter can manipulate this temperature up or down to accommodate the firing procedure or the properties of a glaze that might be applied to the clay, as was the case with Andean Majolicas of the Spanish Colonial Period. Sometimes, even when fired under oxidizing conditions, the clay bodies of pots from non-kiln firings are not always fired hot enough for a duration sufficient for the clay to reach "maturity." Underfired pots are not as strong as fully fired pots and are not water-proof. On the other hand, clays fired beyond their maturity point become brittle and, as the crystal lattice collapses, will eventually lose their ability to retain the shape of the pot (Hamer and Hamer, 1997: 219).

The changes that occur during these different vitrification stages can be seen in the pot's microstructure. The microstructure of a clay body is the "internal arrangement of crystalline and amorphous materials, voids (pores), and the boundaries between them in a polycrystalline and (usually) polyphasic medium'' (Rice, 1987: 348). For ceramic materials this includes temper, voids, and the clay matrix. During the firing, the chemistry of the raw materials, such as fluxing agents that raise or lower the melting temperature and determine the maturation range, interact to form the microstructure. Left unchecked, pottery will go through different phases after the organic material and structural water are burned off, starting with a 'stickiness' of the clay particles and partial destruction of the mineral structure (sintering), progressing to a collapse of the air spaces resulting in a liquid phase and, ultimately, total vitrification (Rice, 1987: 93–94). Differences in the firing schedules (maximum temperature, duration, and speed of the process) between open and closed firing methods require adjustments be made to clay formulations by potters. Clay fabrics designed to withstand a sudden temperatures spike of short duration would not maintain its microstructural integrity in a firing environment characterized by a high temperature sustained for a period of time.

Microstructure, specifically the characterization of vitrification stages, is a good place to start for using pottery to distinguish open and closed firing methods. By studying the microstructure of sherds refired to a known temperature, it is possible to determine the maturation range relative to the refiring temperature for a specific combination of raw materials. In general, a clay body that decomposes at temperatures less than 900 °C soaked for 30 min is unlikely to have been designed for firing in a kiln.

4. Methods

The data set for this investigation contained 60 bowl/plate sherds, including Indigenous slipped (50), Colonial glazed (7), and Colonial slipped (3) surface treatments (Figs. 2–5) hierarchically sampled to represent the stylistic and the technological diversity of the primary collection of 82 bowl/plate sherds from a single excavation unit. All sherds were found at the site of Aqnapampa, a multicomponent site in the southern highlands of Peru, located 80 km southeast of Cuzco. In order to control for variability in the clay formulation related to vessel function and/or size, sherds were selected from bowl or plate forms (non-cookware) with wall thicknesses between 0.4 cm and 0.8 cm, as measured 2.0 cm above the base or below the rim. The sherds were excavated from a 12-level, 2.5 m deep midden considered undisturbed due to the stratigraphic segregation of the major horizon styles: Levels 1–6 contained Colonial glazed and slipped sherds as well as Indigenous slipped sherds; Levels 7–12 contained indigenous slipped pottery only; Levels 8 and 9 contained Late Horizon (AD 1438–1532) decorative styles while one such sherd was found in Level 3; sherds containing decorative elements usually associated with the Late Intermediate Period (AD 900–1438) were found in Levels 1–11 of the primary collection but were sampled only in Levels 1–3, 5, 7–9, and 11; no bowl/plate sherds of any style were found in Level 10. Where possible, sherds were assigned to preexisting decorative style categories.

Based on the presence of horizon styles, the excavation results of Spanish sites elsewhere in the Andes (Jamieson, 2000, 2001; Rice, 1996; Rice and Vanbeck, 1993; Smith, 1991; Van Buren, 1993), and historic analyses (Cornejo Bouroncle, 1960; Rowe, 1944), the following time frames have been assigned to the stratigraphic levels:

Level	Time period
1–6	Spanish Colonial Period (AD 1600–ca. 1800)
7	Early Spanish Colonial Period (AD 1532–1600)
8–9	Late Horizon (AD 1438–1532)
10–12	Late Intermediate Period (AD 900–1438)

The sample preparation procedure used was adapted from those of De Benedetto et al. (2004). After the initial cleaning to remove all visible remnants of the depositional environment, small fragments were broken or cut from the primary sherds with a Dremel hand tool diamond saw. The fragments were further cleaned in a sonic bath (10 min in 50 mL of distilled water), followed by 30 min in a drying oven at 100 °C. The refiring experiment was adapted from Rice (1987). Fragments of each sherd were then aligned in numeric order on kiln shelves and photographed in position before enduring a gas firing under oxidizing conditions that peaked at cone 010 (approximately 890 °C) and sustained at that temperature for 30 min. The refiring temperature (890°) falls in the upper range of what can be sustained by an open firing technology and the lower range of lead-based glazes typical of the Spanish Colonial Period.

An environmental scanning electron microscope (ESEM) with a field emission gun (FEI XL30), a gaseous secondary electron detector (GSED) and a solid-state backscatter electron detector (BSE) was used for imaging and chemical characterization in order to avoid the sample destruction that comes with carbon coating. Microscopy was performed on a sample of the original and refired sherds to evaluate the maturation temperature of the sherds' paste recipes in relation to 890 °C and to compare the micrographs from the original firing and the refiring. Using a scanning electron

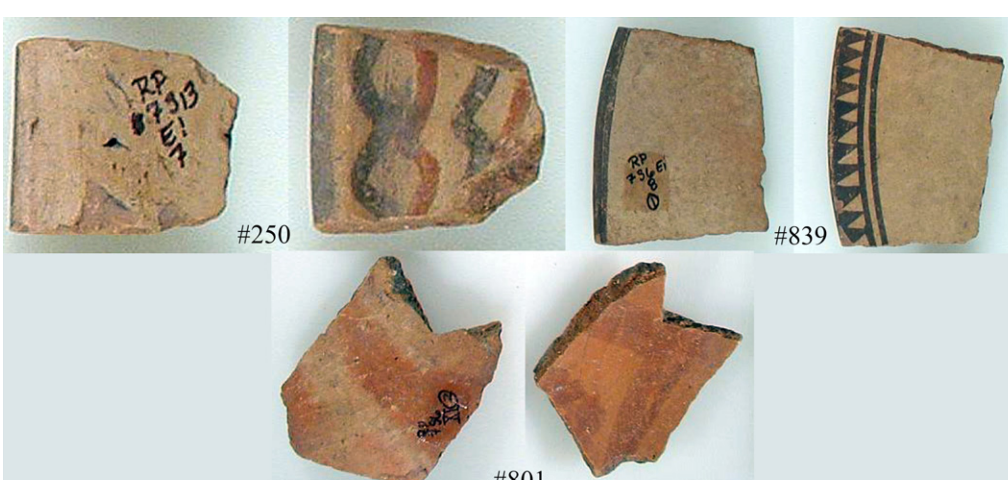

Fig. 2. Examples of slipped indigenous sherds #250, #839, and #801, back and front.

Fig. 3. Examples of glazed sherds #812 and 239, back and front.

microscope, images of the clay body were taken at ×800 and ×5000 magnification as a way of identifying the vitrification structures that developed.

5. Evaluating microstructure

Degrees of vitrification were described with the following codes using the published definitions for calcareous and non-calcareous clays (Buxeda i Garrigós et al., 2001, 2003; Maniatis and Tite, 1981):

NV	No vitrification, clay structure is intact.
NV+	No vitrification, clay plates start to buckle around edges.
IV	Initial vitrification, appearance of smooth surfaces or glass filaments (Fig. 6).
V	Extensive vitrification, areas of smooth surfaces increase in size (Fig. 6).
CV	Continuous vitrification, areas of smooth surfaces connect (Fig. 7).
CV(fb)	Continuous vitrification with a low frequency of fine bloating pores, (0.2–4 μm in diameter) (Fig. 7).
CV(FB)	Continuous vitrification with fine bloating pores (0.2–4 μm in diameter).
CV(MB)	Continuous vitrification with medium bloating pores, smaller pores combine into fewer but larger pores (0.2–10 μm in diameter) (Fig. 8).
CV(CB)	Continuous vitrification with coarse bloating pores, medium size pores combine into a network of a few large pores (10–50 μm) (Fig. 8). Last stage before collapse.
TV	Total vitrification.

6. Results

6.1. *Original firing temperature*

The first part of this study compared microstructures produced in the original firing of a pot with those generated from refiring portions of each sherd to 890 °C. No increase in the degree of vitrification suggested that 890 °C was equal to or less than the original firing temperature for that pot. An increase in the degree of vitrification between the original and refired microstructures implied that the 890 °C refiring temperature exceeded the original firing temperature by degree or duration (see Table 1).

In Levels 9–12, all of the sherds except for one (15 out of 16) in the study increased in their degree of vitrification during refiring, including those styles identified with the Late Intermediate Period, Late Horizon, and regional Late Horizon variants. In Level 8 there was a surge in the diversity of paste types used and decorative styles, although eight of the ten samples exhibited increased vitrification on refiring. Of the two that were unaffected by refiring, one was a Cuzco Inca style sherd (839) that had reached a high degree of vitrification during its original firing, perhaps using an insulated firing technique specific to the Inca pottery workshops. The other example (811) was a Sillustani sherd produced on a kaolin fabric, which is a distinctive white clay used for porcelains and known to have a much higher maturation temperature (1320 °C) than the earthenwares in this study. In Level 7, there was a shift in firing practices where two sherds were influenced by the refiring and four were unaffected. One of those affected was identified as a Killke sherd, a style usually associated with the Late Intermediate Period.

In the remaining stratigraphic levels (1–6), which contained examples of Colonial glazed and Colonial/Indigenous slipped sherds, the refiring process impacted microstructure in two cases. Level 3 contained an example of a Provincial Inca sherd (838), similar to those found in Levels 8 and 9. Because the refired pattern of this sherd duplicated those of Provincial Inca sherds found in the earlier levels, it is possible that this sherd came from a vessel made in the Late Horizon that was curated or used into the later period. It is also possible that this sherd represented the use of an earlier technology in the later period. The decorative style of the other affected sherd (843), found in Level 5, was not identifiable. For the rest of the sherds in Levels 1–6, the initial firing temperature was equivalent to or in excess of the refiring temperature, indicating a change in firing practices that increased the firing temperatures and/or the duration of the maximum temperature sustained.

In summary, based on changes detectable in the original and refired microstructures of bowl/plates sherds in the collection, this part of the study found that the pre-Inca firing technology of Levels 11–12 did not achieve a high level of vitrification in the initial firing,

Fig. 4. Examples of Colonial sherds with rough exteriors and slipped interiors, #824 and #804.

Fig. 5. Examples of slipped indigenous sherds in the Killke style #817, #837, #848, #858, and #870, back and front.

which was conducted at temperatures significantly less than 890 °C. The Inca era (Late Horizon, Levels 8–9) technology achieved increased vitrification in the original firings over those in earlier times, but not to the degree attained by the refiring temperature, indicating that the original firing temperatures were less than 890 °C. Later levels (1–6) contained pottery likely to have been fired in excess of 890 °C.

6.2. Clay maturation temperature

The second part of this study, determining the maturation temperatures of the each paste formulation relative to 890 °C, relied on the degree of vitrification, in large part, but also on the information presented above. Sherd fragments that did not change during the refiring and had been fired to maturity or "overfired" by their original firing yielded no additional information about their maturation temperatures. For the purposes of this study, the microstructure of a clay fabric at its maturation temperature was rated V (extensive vitrification). Refired sherd fragments exhibiting continuous or total vitrification were considered to have been fired beyond the natural maturation temperature for their components (i.e. maturation temperature is less than 890 °C) while refired fragments with no signs of vitrification (NV or NV+) or initial signs of vitrification (IV) were considered to have maturation temperatures exceeding 890 °C.

In Levels 11 and 12, most of the samples in their originally fired state exhibited little to no vitrification. Refiring increased the degree of vitrification to a mature state (one case, 245), while the remaining five sherds from those levels became overfired. In the Late Horizon strata (Levels 8 and 9), most sherds increased in their degree of vitrification with refiring, however most had reached their maturity in the original firing. Notable exceptions include sherd 811 (Level 8, underfired kaolin); sherd 839 (Level 8, overfired Cuzco Inca); and sherd 869, whose maturation temperature was compatible with the refiring temperature. The combined information suggests that the original pots were fired using low temperature, open firing techniques with clay formulation suited for temperatures less than 890 °C.

Levels 6 and 7 contain a mixture of 11 sherds most of which were initially fired to maturity (8) but some of which were overfired (3). The refiring process overfired two additional sherds bringing the overfired total to five. Two sherds had maturation temperatures less than 890 °C, six matured at or above 890 °C, and three were of indeterminate maturation temperatures.

The slipped sherd samples from Levels 1 to 5 exhibited diversity in original microstructure and most were made from clay formulations that were unaffected by the refiring procedure (with the

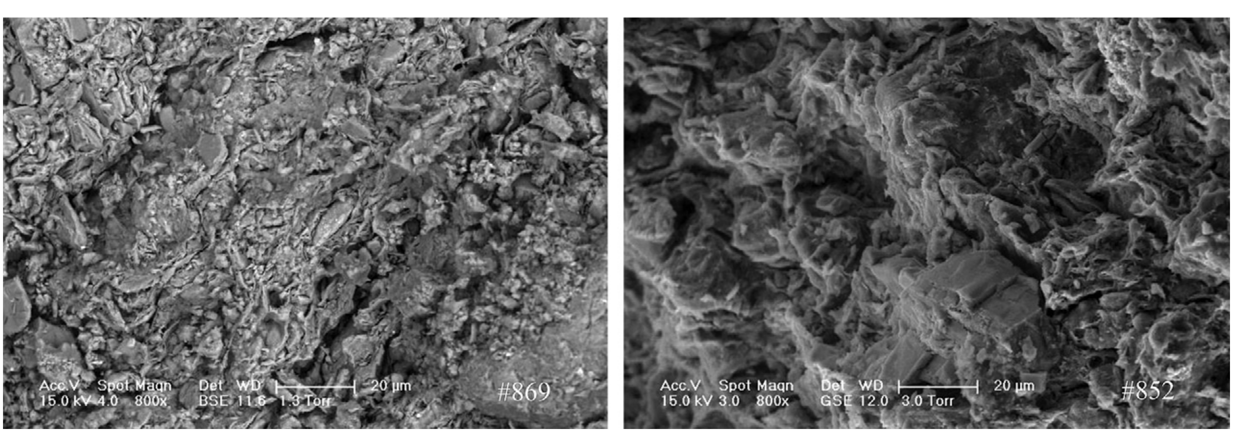

Fig. 6. ESEM photomicrographs of initial vitrification (IV, on left, #869) and extensive vitrification (V, on right, #852).

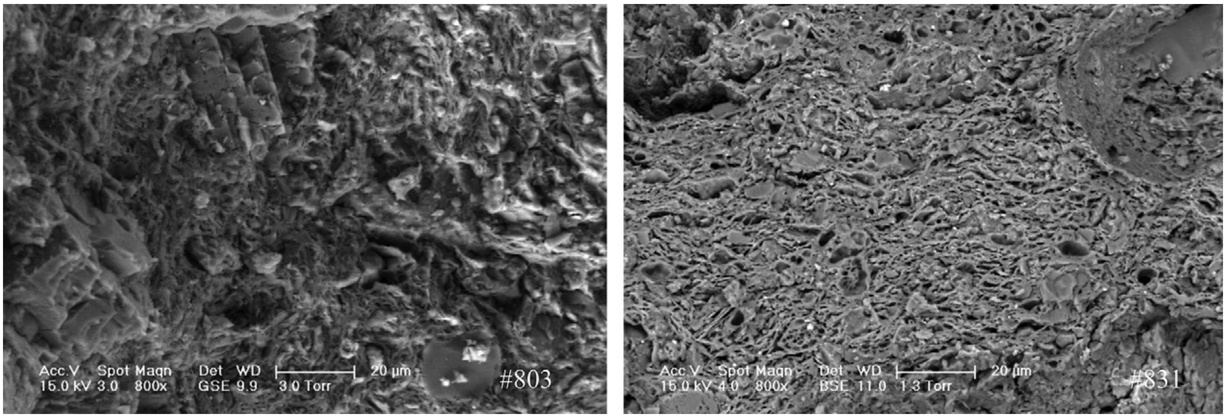

Fig. 7. ESEM photomicrographs of continuous vitrification (CV, on left, #803) and continuous vitrification with fine pores (CV[fb], on right, #831).

exception of the Provincial Inca sherd 838, mentioned above, and sherd 843). Of the 14 slipped samples, nine were overfired in the original firing event, four were fired to maturity and maintained it in the refiring, and one was fired to maturity and refired beyond its limit. Two sherds were altered in their refiring, indicating that their maturation temperature was less than 890 °C. In four sherds that maintained their structure and were fired to maturity, the original firing temperature was equal to or greater than 890 °C. In most cases the sherds were fired beyond their maturation temperature in their initial firing, making it difficult to determine its relationship to the refiring temperature.

Likewise, there was diversity of microstructures found among the Colonial glazed and slipped sherds of Levels 1–5 and the surface. Seven glazed sherds were sampled, most of which were originally fired to maturity and were unaffected by refiring (5), except to revitrify the worn surface of the soft, lead-based glazes. The original firing temperatures for these were estimated to have been greater than or equal to 890 °C. Two glazed sherds in Level 3, though, exhibited opposite traits: one (798) was underfired and continued in that state after being refired while the other (799) was slightly overfired and maintained that structure during the refiring. The maturation temperature of the former was greater than 890 °C while the temperature of the latter was indeterminate.

7. Discussion

From the presentation of the analytical results in their stratigraphic context, it is apparent that there was a general trend toward increasing temperature and/or duration in the firing technologies used at the site of Aqnapampa during the time frame studied (approximately AD 900–1800). In comparing style, surface treatment, relative firing temperature, and relative maturation temperatures of the different paste formulations through time, several technological groupings emerge that point to changes in pyrotechnology and clay fabrics of small bowl/plate forms. The technologies first appeared during the associated time periods, but may have been utilized in later periods as well.

Technological Phase 1: The Late Intermediate Period (Levels 11–12) used an open pyrotechnology that fired pots to a temperature less than 890 °C. As most of the samples had little or no vitrification structures and half exhibited colors in the gray range, it is likely that the pots, from which these sherds came, underwent firing procedures that failed to burn out the organic material. Most of the clay fabric formulations were designed for short, low temperature firings that would not have survived a kiln firing.

Technological Phase 2: Although the Late Horizon levels (8–9) showed a great diversity in decorative styles, there seems to have been greater control over the firing procedure, especially in Level 9 where all the samples came from pots that were fired to maturity. A controlled firing process could be evidence for regional workshops attached to the Inca Empire or a connection to the distribution network of a workshop. While the degree of vitrification of the initial firing increased from the earlier levels, the refiring temperature had less of an impact on these sherds than it had on the sherds of the previous level, suggesting the Late Horizon clay formulations changed. The new formulation increased the maturation

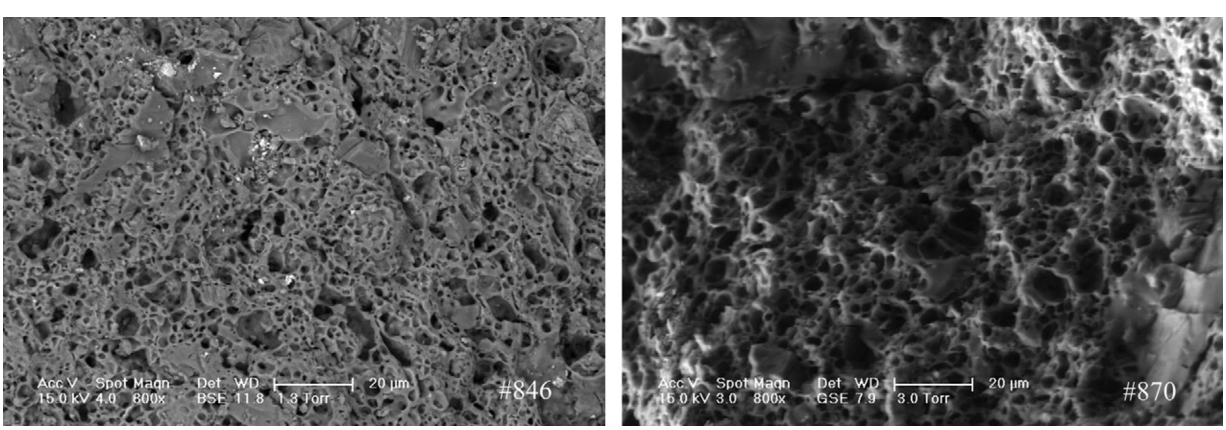

Fig. 8. ESEM photomicrographs of continuous vitrification with moderate bloating pores (CV[MB], on left, #846) and continuous vitrification with coarse bloating pores (CV[CB], on right, #870)

Table 1
Stratigraphic comparison of the extent of vitrification found in the original and refired sherds and an estimation of the original firing temperature in relationship to the refiring temperature.

Sample	Level	Decorative style	Time	Surface	Paste color	Paste color after refiring	As received [A]	Refired [B]	Δ	A/B	Maturation temperature	
1055	0	Tourist	Modern	Glaze	7.5YR 5/3, brown	2.5YR 5/6, red	V	V	=	m/m		≥890 °C
813	1		Spanish Colonial Period	Slip	2.5YR 5/4, reddish brown	10R 5/8, red	CV[FB]	CV[FB]	=	o/o		–
817	1	Killke	Spanish Colonial Period	Slip	2.5YR 4/4, reddish brown	10R 4/6, red	V	V	=	m/m		≥890 °C
824	1		Spanish Colonial Period	Slip, rough	2.5YR 4/3, reddish brown	10R 5/6, red	CV[FB]	CV[FB]	=	o/o	–	–
840	1		Spanish Colonial Period	Slip, rough	10R 5/6, red	10R 5/6, red	CV[FB]	CV[FB]	=	o/o	–	–
859	1		Spanish Colonial Period	Slip	2.5YR 5/6, red	2.5YR 5/6, red	V	V	=	m/m		≥890 °C
815	2	Andean glazed	Spanish Colonial Period	Glaze	2.5YR 5/6, red	2.5YR 5/6, red	V	V	=	m/m	–	≥890 °C
837	2	Killke	Spanish Colonial Period	Slip	7.5R 5/2, brown	2.5YR 6/6, light red	CV	CV	=	o/o	–	–
857	2		Spanish Colonial Period	Slip	Gley 4/N, dark gray	2.5YR 6/6, light red	CV[MB]	CV[MB]	=	o/o	–	–
798	3	Andean glazed	Spanish Colonial Period	Glaze	2.5YR 5/6, red	2.5YR 5/6, red	IV	IV	=	u/u		>890 °C
799	3	Imported glazed	Spanish Colonial Period	Glaze	Gley 3/N, very dark gray	10R 5/8, red	CV	CV	=	o/o	–	–
838	3	Provincial Inca	Spanish Colonial Period	Slip	10R 5/6, red	10R 5/6, red	CV[FB]	CV[CB]	+	o/o	<890 °C	
848	3	Killke	Spanish Colonial Period	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	CV	CV	=	o/o	–	–
854	3	Imported glazed	Spanish Colonial Period	Glaze	5YR 6/3, light reddish brown	10R 6/6, light red	V	V	=	m/m		≥890 °C
855	3		Spanish Colonial Period	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	CV	CV	=	o/o	–	–
795	4		Spanish Colonial Period	Slip	10R 4/4, red	10R 4/6, red	V	V	=	m/m		≥890 °C
803	4	Killke	Spanish Colonial Period	Slip	5YR 3/1, very dark gray	2.5YR 6/6, light red	CV	CV	=	o/o	–	–
828	4		Spanish Colonial Period	Slip	5YR 4/2, dark reddish gray	10R 5/8, red	CV[FB]	CV[FB]	=	o/o	–	–
239	5	Imported glazed	Spanish Colonial Period	Glaze	2.5YR 5/8, red	2.5YR 5/8, red	V	V	=	m/m		≥890 °C
812	5	Imported glazed	Spanish Colonial Period	Glaze	10R 6/4, pale red	10R 6/6, light red	V	V	=	m/m		≥890 °C
826	5		Spanish Colonial Period	Slip	5YR 4/3, reddish brown	10R 5/8, red	V	V	=	m/m		≥890 °C
836	5	Killke	Spanish Colonial Period	Slip	7.5R 5/2, brown	5YR 7/6, reddish yellow	CV	CV	=	o/o	–	–
843	5		Spanish Colonial Period	Slip	10R 5/6, red	10R 5/6, red	V	CV[FB]	+	m/o	<890 °C	
804	6		Spanish Colonial Period	Slip, rough	10R 5/6, red	10R 5/8, red	V	V	=	m/m		≥890 °C
834	6	Provincial Inca	Spanish Colonial Period	Slip	10R 5/4, weak red	10R 5/6, red	CV	CV	=	m/m	–	–
847	6	Local LH	Spanish Colonial Period	Slip	10R 6/6, light red	10R 6/6, light red	V	V	=	m/m		≥890 °C
863	6		Spanish Colonial Period	Slip	10R 5/4, weak red	10R 5/6, red	V	V	=	m/m		≥890 °C
864	6	Local LH	Spanish Colonial Period	Slip	2.5YR 5/6, red	10R 5/8, red	V	V	=	m/m		≥890 °C
250	7	Local LH	Early Spanish Colonial Period	Slip	10R 6/6, light red	10R 6/6, light red	V	V	=	m/m		≥890 °C
852	7	Local LH	Early Spanish Colonial Period	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	V	V	=	m/m		≥890 °C
853	7		Early Spanish Colonial Period	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	V	CV	+	m/o	<890 °C	
866	7	Local LH	Early Spanish Colonial Period	Slip	2.5YR 5/6, red	2.5YR 6/6, light red	V	CV[MB]	+	m/o	<890 °C	
867	7		Early Spanish Colonial Period	Slip	10R 5/8, red	10R 5/8, Red	CV	CV	=	o/o	–	–
870	7	Killke	Early Spanish Colonial Period	Slip	5YR 3/1, very dark gray	2.5YR 5/6, red	CV[CB]	CV[CB]	=	o/o	–	–
243	8	Local LH	Late Horizon	Slip	5YR 4/2, dark reddish gray	2.5YR 4/6, red	V	CV	+	m/o	<890 °C	
257	8		Late Horizon	Slip	10R 5/6, red	10R 5/6, red	V	CV	+	m/o	<890 °C	
810	8	Inca	Late Horizon	Slip	2.5YR 4/4, reddish brown	10R 5/8, red	V	CV	+	m/o	<890 °C	
811	8	Provincial Inca	Late Horizon	Slip	7.5YR 7/1, light gray	10YR 8/1, white	IV	IV	=	u/u		≥890 °C
820	8	Sillustani	Late Horizon	Slip	5YR 4/1, dark gray	2.5YR 6/8, light red	V	CV[FB]	+	m/o	<890 °C	
839	8	Inca	Late Horizon	Slip	10R 5/6, red	10R 5/6, red	CV[FB]	CV[FB]	=	o/o	–	–
850	8	Local LH	Late Horizon	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	V	CV	+	m/o	<890 °C	
858	8	Killke	Late Horizon	Slip	2.5YR 5/6, red	2.5YR 5/6, red	V	CV	+	m/o	<890 °C	
862	8	Inca	Late Horizon	Slip	10R 5/8, red	10R 5/8, red	V	CV	+		<890 °C	
869	8	Local LH	Late Horizon	Slip	2.5YR 6/8, light red	2.5YR 6/8, light red	IV	V	+	u/m		≈890 °C
253	9	LH	Late Horizon	Slip	10R 5/8, red	10R 5/8, red	V	CV	+	m/o	<890 °C	
797	9		Late Horizon	Slip	10R 5/6, red	10R 5/6, red	V	V	=	m/m		≥890 °C
802	9	Killke	Late Horizon	Slip	2.5YR 6/6, light red	10R 6/8, light red	V	CV	+	m/o	<890 °C	
807	9	Chucuito	Late Horizon	Slip	10R 5/6, red	10R 4/3, weak red	V	CV	+	m/o	<890 °C	
821	9		Late Horizon	Slip	5YR3/1, very dark gray	10R 5/6, red	V	CV[FB]	+	m/o	<890 °C	
825	9		Late Horizon	Slip	2.5YR 6/4, light reddish brown	10R 6/6, light red	V	CV	+	m/o	<890 °C	
833	9	Provincial Inca	Late Horizon	Slip	2.5YR 5/4, reddish brown	10R 5/6, red	V	CV	+	m/o	<890 °C	

841	9	Killke	Late Horizon	Slip	2.5YR 5/3, reddish brown	10R 5/6, red	V	CV	+	m/o	<890 °C	
868	9		Late Horizon	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	V	CV	+	m/o	<890 °C	
871	9	Local LH	Late Horizon	Slip	10R 5/8, red	10R 5/8, red	V	CV[MB]	+	m/o	<890 °C	
245	11	Tiwanaku	LIP	Slip	10R 4/6, red	10R 4/8, red	IV	V	+	u/m		≈890 °C
801	11		LIP	Slip	Gley 5/N, gray	2.5YR 6/6, light red	V	CV[MB]	+	m/o	<890 °C	
808	11		LIP	Slip	Gley 5/N, gray	10R 6/6, light red	IV+	CV[FB]	+	u/o	<890 °C	
846	11	Killke	LIP	Slip	Gley 4/N, dark gray	2.5YR 6/6, light red	NV+	CV[MB]	+	u/o	<890 °C	
872	11	Killke	LIP	Slip	10R 6/6, light red	10R 5/8, red	IV	CV	+	u/o	<890 °C	
831	12		LIP	Slip	2.5YR 6/6, light red	2.5YR 6/6, light red	IV	CV[fb]	+	u/o	<890 °C	

temperature, although the optimum firing temperature remained less than 890 °C. Greater control over the pyrotechnology, as evidenced in consistently fired pots, indicates that there might have been a technological development that facilitated the firing process, such as an insulated or semi-subterranean structure that afforded control and protected the low-firing clay.

Technological Phase 3: In the Early Spanish Colonial level (7) and Spanish Colonial Level 6, there was an abrupt end to the stylistic diversity found in the previous level and the start of clay fabrics formulated for closed firing procedures. Local styles dominate this timeframe, over half of which were fired to maturity in the initial firing. Control over the firing process continued. There were three examples that were overfired initially but most had maturation temperatures over 890 °C. The initial firing temperatures were greater than or equal to 890 °C. There was a consistency to the firing practice that yielded well-fired pottery in the local style that did not continue into later levels.

Technological Phase 4: The final technological grouping appeared in the later Spanish Colonial levels (1–5), when there was more diversity of wares, but less control over some aspects of the process: either the initial firing procedure was unpredictable or the clays used were varied (sources or potters). Although there are examples of clays reaching maturity, there are many that were extremely overfired (Indigenous and Colonial slipped) at initial temperatures greater than 890 °C. Because so many were overfired initially, the maturation temperatures cannot be determined. Most were fired using closed methods, many with clays formulated for higher temperatures. It is possible that firing was a communal event during this period and pots were made in various households using non-standard clay formulations.

In addition to the patterning that formed technological groups in the collection, there are technological changes that can be followed within decorative styles. Originating in the LIP, Killke sherds were found in multiple stratigraphic levels of this unit, suggesting either curation of the pot or continuation of the earlier pottery technology into later times. During the LIP (Phase 1), Killke sherds (two) were underfired (NV+ and IV) initially using low-firing clays in open bonfires. Firing to 890 °C increased vitrification structures, indicating that the maturation temperature was below that temperature. Phase 2 Killke examples (three) behaved as the rest of the styles in this technological grouping did: they were fired to maturity during the initial firing (V) and slightly overfired during the refiring (CV). Compared to the degree of vitrification of the refired fragment in the previous phase, these Killke examples are made of clay with a slightly higher maturation temperature, although it is still less than 890 °C. The next technological phase (3) saw an overall shift in clay formulations to maturation temperatures greater than 890 °C. A Killke sherd in this grouping was extremely overfired initially, exhibiting the highest degree of vitrification of any sherd in the study (CV[CB]). It is likely to have been manufactured using a Phases 1 or 2 recipe in a Phase 3 firing structure. In Phase 4, Killke examples occurred in each level with Spanish pottery. In Levels 2–5 the Killke sherds were slightly overfired in the initial firing (CV) to a degree that remained unchanged after refiring. This was a break in the technological pattern of Killke sherds in the previous technological phases, so it is likely that the sherds were fired using the contemporary, closed technology with a paste formulation that was not quite right for the method. However, in Level 1 there was a Killke sherd, fired to maturity initially and maintained that degree of vitrification after the refiring, suggesting that the paste was reformulated for the higher firing temperatures attained in contemporary (Phase 4) firing practices. This technological data for changing firing practices, as seen through original soaking temperatures, and clay recipes, as determined from relative maturation temperatures, argue for continued production of the Killke style using evolving techniques (Chatfield, 2007).

8. Conclusion

The results of this study have significant implications for the study of Inca origins in the Cuzco region. Commonly used as a chronological marker for the LIP, the Killke style is thought to have been the stylistic antecedent to the Inca style produced during the Late Horizon in the imperial heartland. However, rather than adopting new pottery styles, these indigenous potters retained their traditional styles while adapting to new potting technologies. The current use of the Killke style as a marker for the pre-Inca period has overstated the LIP occupation of the Cuzco area but more importantly, it has obscured indigenous colonial contexts that could contribute to our knowledge of the historic era of Peru. While style is proving to be a problematic temporal indicator in the Cuzco region, firing technology promises to be a more accurate chronological marker during this critical and little understood transitional period of the Andean past.

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