Reedy, C., Vandiver, P., He, T., Xu, Y., & Wang, Y. (2017). Research into Coal-Clay Composite Ceramics of Sichuan Province, China. *MRS Advances*, 1-37.

DOI: 10.1557/adv.2017.286

Research into Coal-Clay Composite Ceramics of Sichuan Province, China

Chandra L. Reedy [1], Pamela B. Vandiver [2], Ting He [3], Ying Xu[1], and Yanyu Wang[3]

[1]Laboratory for Analysis of Cultural Materials, Center for Historic Architecture and Design, University of Delaware, Newark, DE 19716, U.S.A.
[2]Department of Materials Science and Engineering, University of Arizona, Tucson, AZ, USA
[3]Sichuan Provincial Institute of Cultural Relics and Archeology, Chengdu, China

ABSTRACT

A group of traditional pottery workshops in Sichuan Province, China, produce a unique coal-clay composite ceramic that is fired using a similarly unique kiln design and two-stage firing procedure not seen in any other ceramic tradition. Here we report on field and laboratory efforts to better understand this unusual ceramic material and technology, the functional advantages as cookware, braziers, and large storage vessels that include high strength and high thermal shock resistance, and the cultural context that supported the creativity and experimentation needed to develop such an innovative technology.

INTRODUCTION

In 2014 our American-Chinese team began a survey of the remaining traditional pottery workshops of Sichuan Province, China. We encountered workshops producing a ceramic material not previously known from any geographic context: a coal-clay composite made of about half powdered coal cinders and half clay. Firing is performed with a unique kiln design and a rapid two-stage firing procedure not documented at any other location, in China or elsewhere. Potters use a round in-ground, coal-fired primary kiln with a shallow pit and a removable, hemispherical-shaped, metal-reinforced ceramic cover. Pots are removed when sintered to yellowish-orange heat and are placed in a deep pit-kiln, called a glaze kiln or *yòu kēng* that is also in-ground and next to the primary kiln. Organic material is added, and the pit-kiln is closed with a metal cover. Reminiscent of American interpretations of Japanese raku kilns, the organic material burns rapidly in reduction and forms a natural ash "glaze" on the exposed surfaces of the pottery. Pots cool rapidly, prior to removal, because water is introduced into a chamber surrounding the kiln. The entire firing cycle from room temperature to about 1150°C and back to room temperature takes only about 85 minutes. The thermal-shock resistant clay body made of coal cinder and clay that is subjected to the special two-stage firing procedure results in a hard, black ceramic with a shiny, silvery, and sometimes bubbly surface (Fig. 1).

We found two locations in Sichuan Province where these unique ceramics are made: Yingjing, in central Sichuan, southwest of the capitol city of Chengdu; and Gaoxian, in southeastern Sichuan bordering Chongqing Municipality (Fig. 2). The potters in both locations claim a long, 2,000-year-old history to their materials and procedures, and we are currently investigating the chronology and source of this tradition in the black, sometimes polished, earthenware. Here we report field and laboratory studies of the raw materials and their processing, pottery fabrication techniques, firing schedule and kiln designs, microstructural and compositional characteristics, material properties, and uses of resulting ceramic products, along with design issues and product variability, and some functionally interesting performance characteristics. The goal is to reveal the properties and functional advantages of the unusual and innovative technological choices made at these two locations. We are interested in understanding how and why such unique materials and firing methods emerged here and how they fit in with other cultural developments of the region, such as innovative cuisine and dining practices.

Figure 1. Coal-clay ceramics with an ash glaze are black with a silvery, bubbly surface texture.

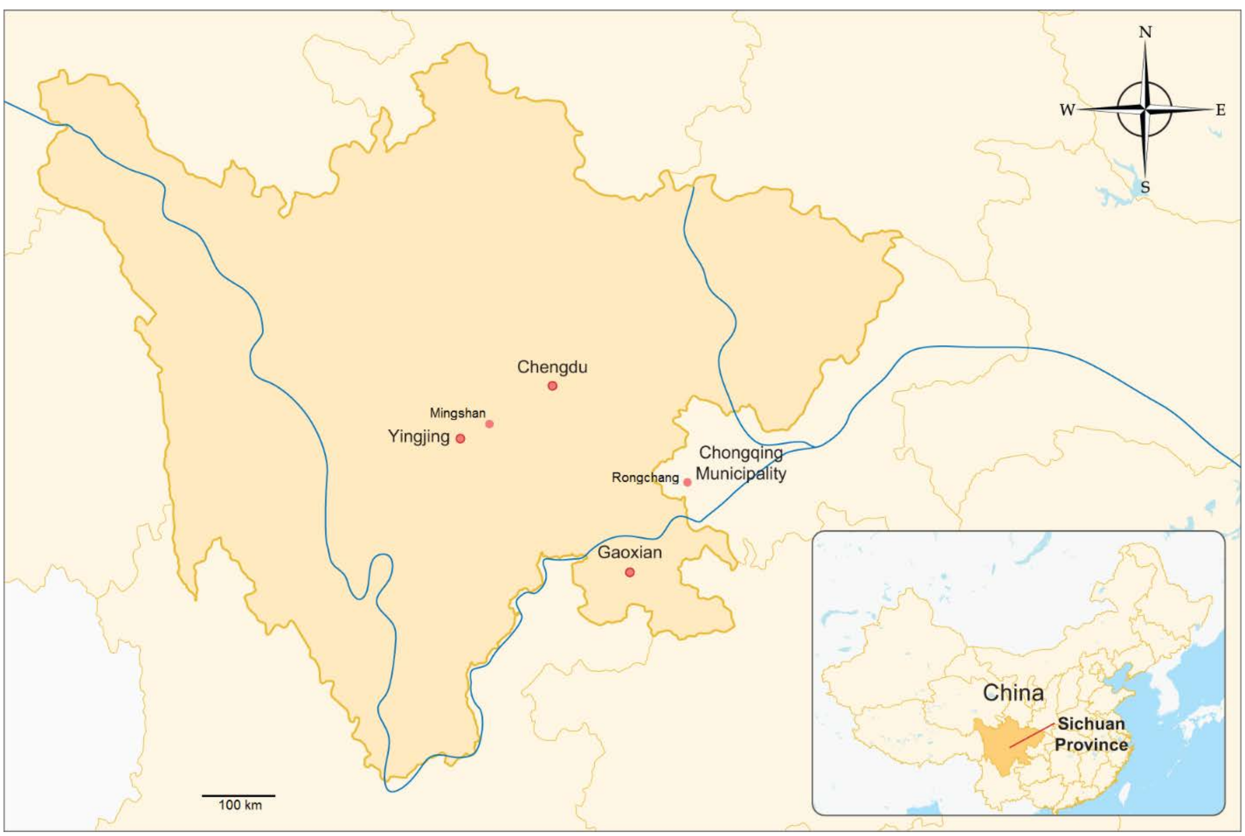

Figure 2. Ten kilns are located in Yingjing and one in Gaoxian, Sichuan Province, China.

RESEARCH METHODS

In 2014-15, three field visits were made to Yingjing, and one to Gaoxian. During these field investigations, raw material use and processing, workshop organization, pottery fabrication methods, kiln designs and firing procedures, and product types and marketing strategies were studied. Methods included observation, participant observations, interviews, photography and videography, and collection of examples of raw materials and pottery in various styles and stages of manufacture, including wasters (with more in-depth research conducted to date in Yingjing).

Materials and objects were analyzed in the laboratory by a variety of methods. Raw materials and sherds, minerals, and other non-plastics were identified and studied qualitatively under transmitted polarized light by thin-section petrography using a Nikon Eclipse 50i POL microscope system [1]. Thin sections were prepared using a blue-dyed epoxy to readily distinguish pores from clear minerals, and were then scanned at a resolution of 2.54 µm/pixel (10,000 x 10,000 dpi) for quantitative image analysis using Image-Pro Premier by Media Cybernetics [2, 3]. Total optical porosity, pore size (Feret diameter), and shape were measured. Inclusions were examined, and the variation in ash glazes was investigated, including presence, porosity, thickness, phases present, and nature of glaze-body interface.

Other techniques often used in the study of ancient and historic ceramics [4, 5] employed were scanning electron microscopy with energy dispersive X-ray analysis (Hitachi S3400 SEM and S4800 FESEM, both with ThermoNoran EDS system and NSS software), electron probe microanalysis (Cameca SX100 5-spectrometer probe with backscattered imaging and EDS), refiring tests to 1200°C in air and in nitrogen for reduction firing (Thermolyne 1700 Box Furnace), and differential thermal analysis (Perkin-Elmer 1700 DTA). We also performed measurements to examine open porosity (ASTM C 20-74) and gloss (Horiba IG-410 Gloss Checker). Hardness testing used the Mohs hardness scale, measured by scratching the surface with a mineral for each hardness number using the procedure recommended to us by Fred Matson [6]. The Mohs stone was first used to scratch the pottery, and then both surfaces were observed for traces of the softer material at 10-30x using a stereomicroscope (Leica E74). The reverse procedure was then performed, with the pottery scratching the stone, followed by similar stereomicroscope observations. Intact objects were imaged with Xeroradiography (Xerox Medical Products Xeroradiograph 125) to examine the internal structure and distribution of particles and pores resulting from material textures, fabrication methods, and flaws [7]. Performance characteristics were studied by using pots for their intended cooking and serving functions and observing the results; in particular, the thermal expansion and shock resistance.

RESULTS AND DISCUSSION

Workshops: Pottery Village vs. Lone Workshop

Yingjing. In Yingjing, a group of 10 kilns with associated workshops, making relatively similar products, are located in the administrative seat of Yingjing, on a single street in the "old town" section, *Gǔ chéng cūn,* in an area of town known as *Liù Hē* village, and also known as Black Sand Pottery Village in local records and on historical markers (Fig. 3). The 10 kilns support 15 workshops plus sales rooms, and another 17 workshops located away from sales areas. There are also clay storage areas, fuel (coal) storage areas, and a few shops without attached workshops.

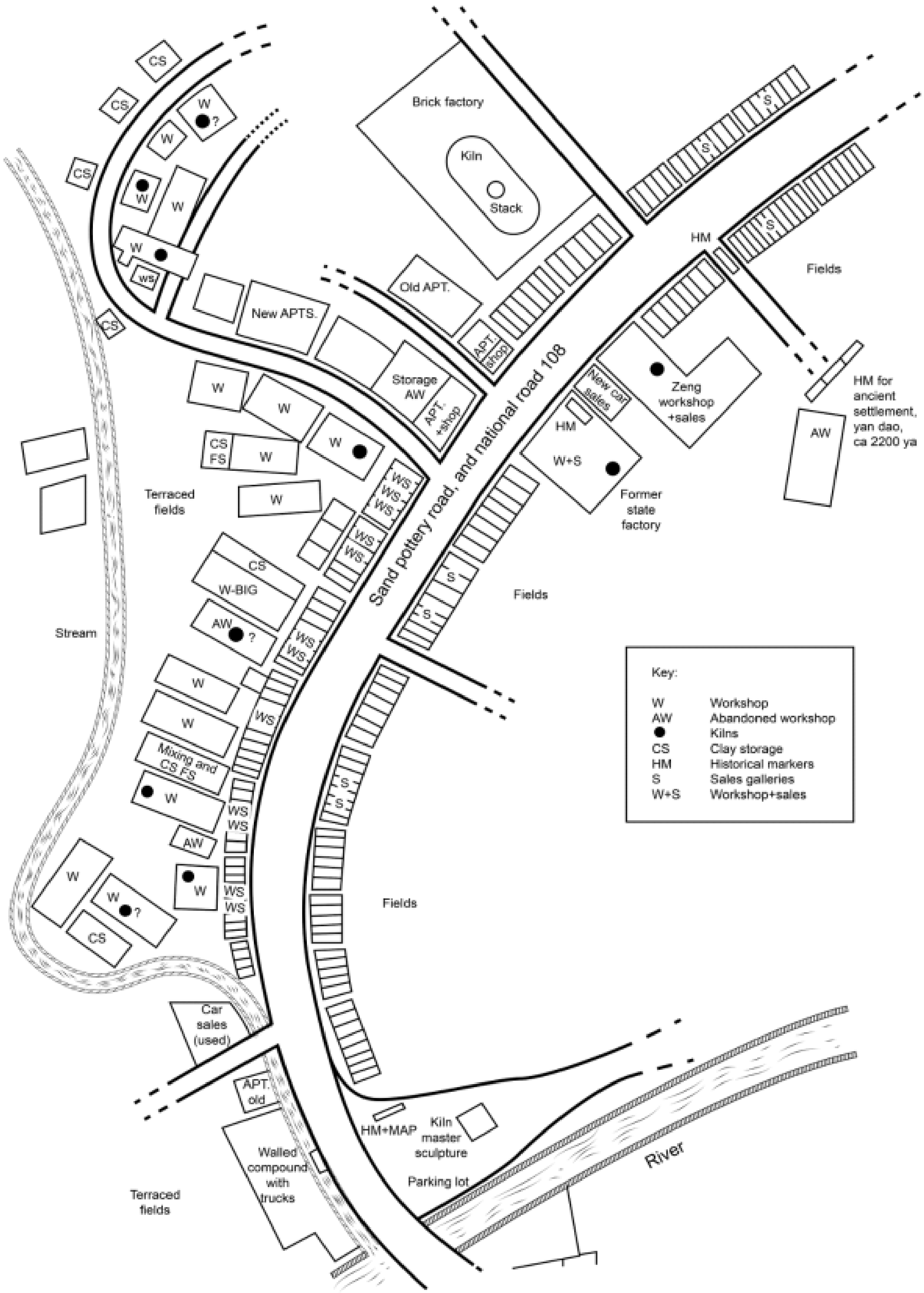

Figure 3. The pottery street in the “old town” (*Gǔ chéng cūn*) area of Yingjing.

In a workshop owned by Zeng Qinghong, we were able, on multiple occasions, to observe each step in the clay preparation, fabrication, firing, and finishing process, as well as interview the owner and other potters and decorators. For comparison, we were also able to conduct interviews and observe processes at two other workshops located nearby, those owned by Gujing Ping (next to the Zeng workshop, at the location of the former State Factory) and Zeng Dou (across the street from the Zeng and Ping workshops). While these are all family-owned workshops, each also has a number of employees.

In the workshop where we spent the most time, the master potter and workshop owner, Zeng Qinghong, comes from a family of potters. He has run this workshop for over 30 years and reports that his family has been making coal-clay pottery here for many generations. His workshop employs 20 workers in various steps of pottery production, a combination of family members and local people.

Mr. Zeng estimates that 20 years ago there were more than 100 kilns on the pottery street; now there are only 10. He speculates that the reason for the recent disappearance of kilns and their associated workshops is that costs for raw materials and for contracting workshop personnel have risen greatly in recent years, so it is more difficult for a workshop to be profitable. As a result, many local potters now go elsewhere as migrant laborers to work in potteries in other towns, or they work in Yingjing as hired labor instead of operating their own workshop. However, he notes that many young people in town still learn to make this type of local pottery at home, practicing by themselves and/or observing other people making the traditional coal-clay pottery. He believes that if it were to become profitable again to run a workshop, more people would once again want to establish their own. To encourage the longevity of local pottery production, he rents out parts of his factory to potters, sculptors, and artists and allows them exhibition space in his gallery. Investigating the history of kilns and pottery production in Yingjing, and the reasons for changes over time, will be part of our future research agenda.

Gaoxian. In Gaoxian County, there is only one coal-clay pottery workshop, a small family-run enterprise located on the outskirts of the town. The sole potter is the owner, Huang Bin Xue. He is assisted in some operations, such as firing, by his wife, but there are no employees or other family members involved, and no apprentices. His son is away from home studying computer engineering. No other traditional pottery workshops, making coal-clay or any other products, are known in this county, although investigating if more were located here in the past is part of our future research program. The potter says that this workshop has been in his family for three generations, more than 100 years, and that they have always added coal cinders to their clay body and fired in the two-stage process. Our time here was limited as the presence of coal-clay pottery technology was a surprise discovery, so more in-depth study is planned here as part of our future research agenda.

Raw Materials and their Processing

Yingjing. One of the main raw materials is inhomogeneous sandy yellow clay obtained locally from agricultural fields below the plow zone and purchased from farmers, usually when they need to relevel a field for better irrigation and drainage. Thin-section petrography, supplemented with DTA of the fine fraction, indicates that it contains a significant amount of fine-grained quartz, illite, and organic matter. Accessory phases are iron oxides and a small amount of chlorite (Fig. 4). For most objects, this clayey material is coarsely ground. For a few types of products where a more fine-grained material is desired (mainly teapots and tea cups), the yellow clay is more finely ground and is mixed with a pale yellowish white clay imported from Mingshan, a district under the administration of Ya'an city, 50 kilometers north of Yingjing (Fig. 3). This finer clay has very fine-grained quartz with accessory sericite, and fewer organics and iron oxides than the yellow clay, and this more fluxed clay melts to a glass at 1100°C.

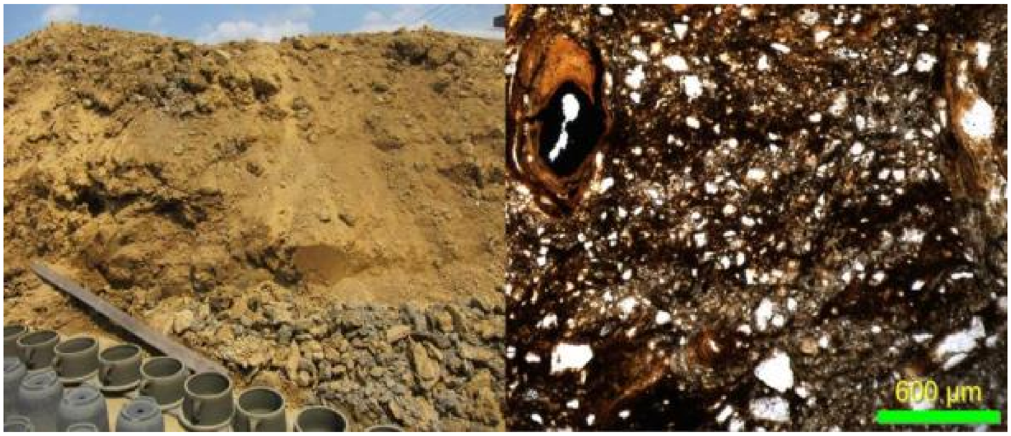

Figure 4. Yellow clay (left) purchased from farmers is rich in illite, quartz, and organic material, along with iron oxides and accessory chlorite mica; right shows a thin section of the yellow clay in plane polarized light.

The clay is mixed with burnt coal, obtained both from within the workshop itself (that is, coal that has been used to fire the kiln), and from a variety of external sources in Chengdu and Chongqing. This burnt coal is carefully sorted into "qualified" material selected for use versus "unqualified" material that is discarded. Mr. Zeng makes this determination by eye himself for the coal cinders generated by his own kiln. For coal purchased externally, his suppliers bring samples to him to check if they qualify. "Unqualified" coal cinder (Fig. 5, left) is very heterogeneous with carbonized cores surrounded by partly crystallized glasses. We found porous and layered organic structures comprising shreds of well-preserved woody material at the cores, filled with highly carbonized areas and punctuated by quartz particles, many of which are cracked, partially melted, or transformed to cristobalite. Most of the silica phases are concentrated in glassy areas around the edges, and include clay patches permeated by long and slender mullite needles, isotropic feldspar remnants covered with thicker rods of mullite, areas filled with well-developed and twinned anorthite rods, cristobalite, pools of silica glass, and very small rounded and partially melted quartz remnants set into glassy areas. In contrast, the "qualified" coal cinder (Fig. 5, right) is more homogeneous overall, with more clay, organic structures, and silica minerals than glass. These are distributed more evenly throughout the material. It lacks the large glassy areas on edges, and contains fewer larger areas of mullite and anorthite. Instead, it has more clay and a complex mineralogy with quartz, polycrystalline quartz, microcrystalline quartz (chert), cryptocrystalline quartz (chalcedony), anhydrite, and a few incompletely melted plagioclase feldspar grains and muscovite remnants. The material is less porous overall than the "unqualified" coal cinder. The careful selection of this more homogeneous coal cinder with much less glass and porosity is important during firing because the chosen coal cinders will resist plastic flow, warping, and deformation; whereas glassy aplastic inclusions during firing will continue to flow.

In the clay body preparation room, the coal cinders are ground and the clay is disaggregated by milling in a jaw crusher. The potter notes that this is a new time saver, as the workshop used to mill clay by the traditional Chinese method of a horse pulling a milling stone through a stone trough. The milled clay and ground coal-cinders are measured volumetrically with a scoop, piled on the grinding room floor, shoveled together, and then thoroughly wetted (Fig. 6) (water not yet analyzed). The ratio of the mix for most products is 50-50. For the few fine products that incorporate the white clay, all raw materials are more finely ground in a second grinding step to the consistency of flour using a flour mill. The mix proportions are 3 parts coal cinder, 3 parts local yellow clay, and 1-1.5 parts white clay. The wet coal-clay powder is further mixed and de-aired in a pug mill, and the fineware mix is processed wet in a ball mill. Then they are taken into the potting rooms to set for a period of days, allowing the clay to wet through and the plasticity to increase. The fineware body will become a high-fired, impermeable earthenware, and the coarseware body will become a high-fired stoneware.

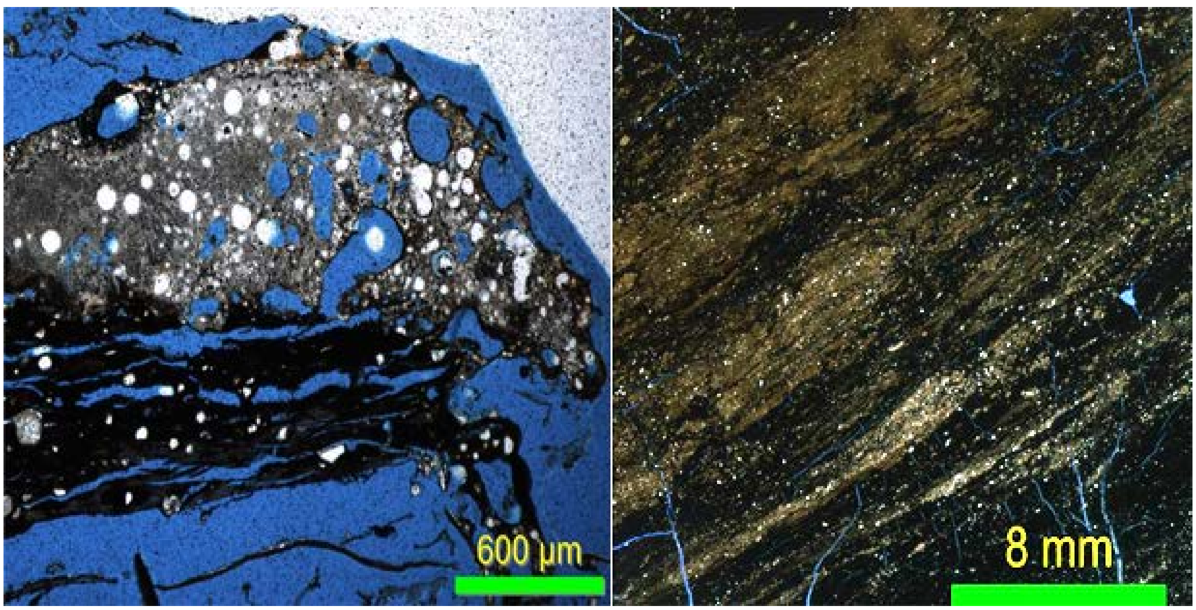

Figure 5. Yingjing "unqualified" glassy coal cinders with carbonized material below and mixed glass, pores, and crystalline phases above (left); and more homogeneous, low-glass phase "qualified" coal cinders (right).

Gaoxian. In this workshop, the potter collects the clay himself from the nearby mountains, paying the landowner for it, and, once moved, he dries it for several weeks. The clay is black in appearance and smells of a high humic or organic content (Fig. 7, left). DTA of the fine fraction indicates the clay is most likely an illitic ball clay. In thin section in plane polarized light, the clay is brown and inhomogeneous with carbon and iron oxides appearing as long black streaks and smudges and particles of various sizes. Very fine-grained silt and sand are distributed throughout the clay matrix, comprised mainly of quartz. Organic material, often partially or fully carbonized, also is present. As shown in Fig. 7 (right), some of the organic structures and veins within the clay have been partially replaced by precipitated silica, as microcrystalline chert, cryptocrystalline chalcedony, or colloform opal; and sometimes the replacement mineral is calcium carbonate.

Figure 6. Yingjing grinding room, where milled clay and selected, ground coal cinders are mixed together and then wetted and pugmilled before use in the potting rooms.

This workshop adds to their clay body only the burnt coal from their own kiln. They do not have sufficient need to require purchasing coal cinders from other sources. No sorting into "qualified" or "unqualified" coal cinders occurs. However, the potter says that he deliberately chooses "softer" coal as fuel for his firings, because, after burning, these cinders are better for use in pottery than is "harder" coal. The softer coal may be easier to grind after the firing. Before burning in the kiln, the raw coal they use consists of very compact carbonized material with scattered fine-grained, rounded quartz, and many large organic structures filled with replacement silica and calcium carbonate. The forms of the organic structures are mostly obscured by the pervasive black carbon except in larger ones where there is replacement silica or calcium carbonate that highlights the structure (Fig. 8).

Their coal cinders, pulled from the kiln after use in firing, are much more porous and heterogeneous than the original raw coal (Fig. 9). The center region of the cinder is very carbon-rich, punctuated with quartz grains and microcrystalline and cryptocrystalline silica. The outer edges of these coal cinder chunks, however, are a quite porous silicate glass with many areas that are rich in clay and carbon. On the interior edges, iron-rich patches of clay have small elongated needles of mullite. Clay patches that extend further into the glass are filled instead with slender needles of anorthite that grow from the clay into the glass matrix. Large glass regions are filled with longer and thicker needles and laths of anorthite, interacting with iron oxide in the surrounding glass to form feathery and dendritic structures of anorthite with precipitated iron oxide at and around the edges and spaces between the anorthite. These structures are similar to those seen in southern Chinese black glazes that are rich in lime and iron oxides, as for instance, those from Jianyang [8]. Within the outer glassy layers are large patches of cristobalite. Clearly, the outer edges of the coal cinders get much hotter in the kiln than do the centers of the coal fragments. This inhomogeneous material is closer to the Yingjing "unqualified" coal cinders, although it is mineralogically somewhat different.

Figure 7. Black Gaoxian illitic clay (left) is filled with iron oxides and carbonized organic material; some of the organic structures are filled with secondary calcium carbonate (right) as shown in this thin section in plane polarized light that has been stained for calcium carbonate.

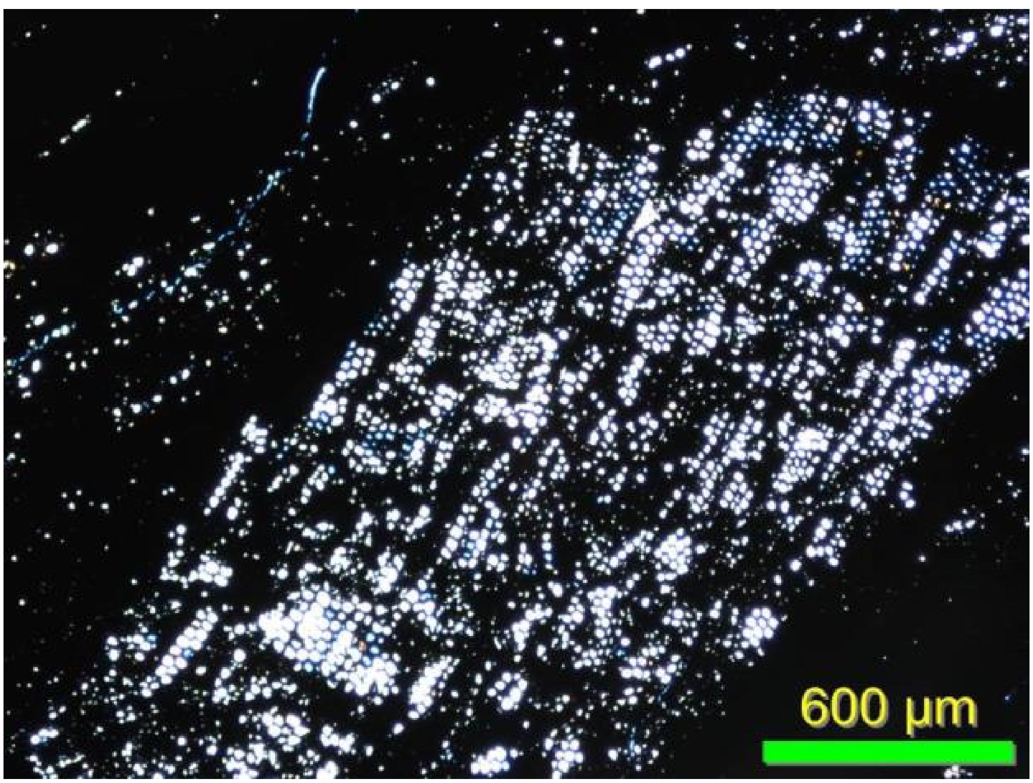

Figure 8. Raw coal in Gaoxian is a compact carbonized material with large organic structures filled with replacement silica, as seen here in crossed polarized light, or with secondary calcium carbonate.

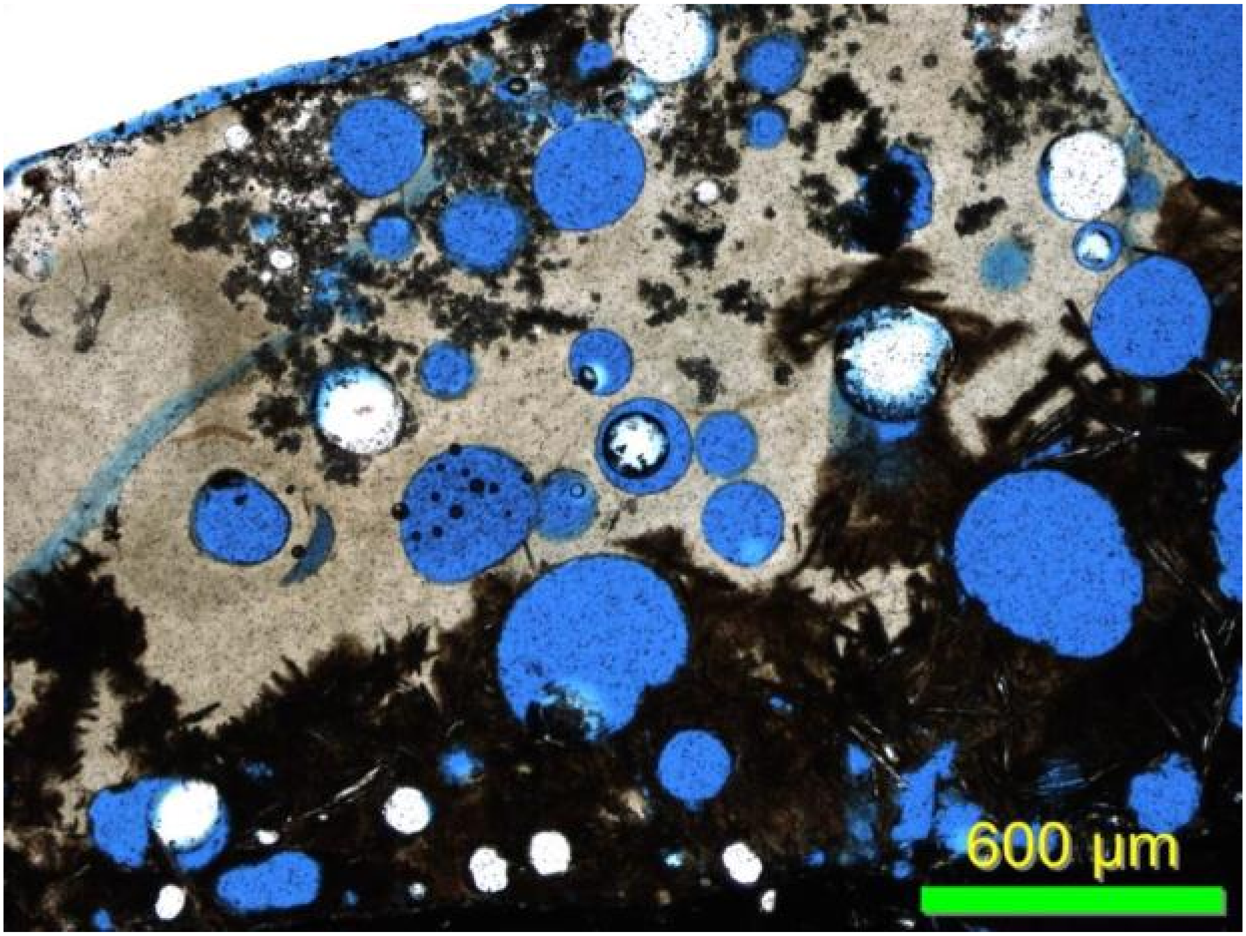

Figure 9. Inhomogeneous burnt coal in the Gaoxian workshop, with large round pores, glassy surface layer, and high-temperature minerals forming at the glaze-body interface and other boundaries.

The dry clay and coal cinders are ground together in a hand-operated grain mill, rather than ground separately as in the Yingjing workshops. The proportion of coal cinders used here is lower than in Yingjing, 30 vol% coal cinders to 70% clay. Differences in the raw materials, firing schedule, and/or products may account for the different proportions used in the two clay body recipes. Once the Gaoxian clay and coal-cinder body is in the form of a well-mixed fine powder, it is wetted and taken to the potting shed for storage and use.

Fabrication and Production Cycle

Yingjing. Most items are fabricated on a low kick wheel onto which pots may be stacked or removed to raise or lower the height as needed depending on the task (Fig. 10). Vessels are built up on the wheel by specialist potters who also make lids but do not carry out any decorating. Potters use a combination of mold construction, coiling, paddling, and wheel building, aided by many homemade tools. It takes about 20 minutes on two different days to make a typical vessel, although this varies according to the type of object being made. The objects are then allowed to dry to stiffness for about a half-day inside the pot shop and are then decorated. The potters we observed were all male; however, a woman who specializes in decorating the vessels noted that she had the opportunity to build vessels as well, but chose not to, since it required regularly carrying large piles of wet clay to her work station.

The work then moves on to specialist decorators, mainly women. The decorators add spouts, handles, and decorative appliqués, such as the dragons that have caught the flaming pearl of immortality and thus are considered lucky for soup pots, as shown in Fig. 11. The decorative specialists perform only this part of the process. Some objects also receive incising and/or rouletted decoration, as in Fig. 11, but this is done at the wheel-throwing workstation.

Figure 10. Master potter Zeng Qinghong (left), assembles a teapot above a kickwheel on a raised working surface; another potter (right) is adding coils to a mold-formed base made the previous day. He has chosen a lower-height working surface on which he will add two coils, then paddle and throw each, to build the walls and form the rim of a rice pot, one of 50 or 60 he will complete this day, and similar to the one with floral decoration below the teapot (left).

The finished objects are allowed to dry indoors or in the courtyard for at least five days, and for as long as two weeks, depending upon the weather. When almost ready for firing, objects are preheated by being placed on a shelf above the kiln, or hung on racks at the back wall of the kiln room, for at least one burning of the kiln, or placed beside the kiln to dry excess moisture before the firing process begins.

A detailed chart of the work schedule is given in Table I. It outlines a minimum two-week cycle that produces about 60 decorated and lidded soup pots in the Zeng workshop. In reality, days five through eight are repeated at least five times until sufficient pottery is made for a day of five or more firings.

Gaoxian. As in Yingjing, a low kick-wheel is used for fabrication (Fig. 12, left). Vessels are constructed with a combination of molds and coil building. The lone potter, Huang Bin Xue, makes all of the vessels and lids, and also does any simple decorative work, which is more limited here than in Yingjing. Most pots receive no decoration other than the ash glaze surface. Fabrication and decoration steps are accomplished with a variety of home-made tools (Fig. 12, right). Finished objects dry for about a week, stored out of the way and with good air circulation on ceiling racks inside the potting shed.

Figure 11. In Yingjing, dragon appliqués and bands of rouletted decoration are popular; most appliqué and additions of spouts and handles, are completed by women who specialize in this decorative step. However, note that Fig. 10 left shows a special commission of about 15 teapots that are being completed by Mr. Zeng, including the steps of adding the spouts and handles.

Figure 12. Gaoxian master potter, Huang Bin Xue, builds a brazier or "Sichuan hotpot" on a low kick wheel (left). The clay body supply is to the left and water is to the right. His hand-made tools (right) are kept near the workstation (a large brush to add and spread water, hook to shape joints, knife, trimming tool, and needle tool).

Table I. Pottery Production Cycle at Zheng's Yingjing Pottery: Example of a two-week cycle that produces 50-60 decorated and lidded-soup pots is recorded. In practice, the forming processes are repeated until enough pots are produced for at least five firings of 60 pots each that can occur in one set of two kilns in one day of firing (See Table III for the firing schedule).

PREPARATION: Day 1 and more days, if needed, depending on numbers of workers available. Sorting of coal ash to select that with the least amount of glassy phases is done in material storage area. Elimination of the glassy phases makes the pottery less susceptible to thermal shock when rapidly heated, and is critical to lower losses and to achieve success.
Day 2. Coal ash grinding and clay disaggregation by milling is conducted in material preparation area.*
Day 3. Clay and coal ash are mixed, followed by addition of water, pug-milling, and loads of the clay body are moved to work stations in the production area.*
Days 4 and 5, or more. Setting of the plastic-covered clay body to promote plasticity.

FORMING AND DECORATING SOUP POTS: Day 6. Throwing using a fast kick-wheel of 100 soup pots on a convex or male mold attached to a circular batt, or wooden board. For many vessels, such as the soup pots, two clay bodies are used with the exterior one having a finer texture and particles. One body is combined with the other, as if in a two layer sandwich or pancake, patted out, then pressed and paddled and then thrown over the fired-clay mold. Then they are set aside to dry until just short of leather hard.
Day 7. They are removed from the molds. The upper one third of each soup pot is formed by joining a single large coil, then paddling to even wall thickness, and then throwing to raise and incurve the wall. A second large coil is joined, paddled, and thrown to form the rim and lid supporting flange.* The pots are moved to the decorator's work area. As soon as they are stiff and just short of leather hard, in summer in about half a day, they are decorated with dragon, plant and flower, or other motifs, using the finer clay body.
FORMING AND DECORATING LIDS: Day 8. 110 lids are thrown, upside-down. The 10 excess lids are thrown to allow for breakage. A flat and bottomless cylinder is thrown, and an overhanging rim formed and then closed and flattened.*
Later in day 8 or on day 9, depending on the weather and especially on the relative humidity**.** The lids are finished by adding a knob that is thrown to a flattened shape. Decoration is added at the wheel by rouletting, the pottery's stamp is pressed into the lid's outer surface, and a small hole for steam from the soup is made. The lids are then moved to the decorating area for dragon, plant, or other decoration.

DRYING PERIOD: Days 10-14, or more. Drying period, if it is not raining such that firing is delayed.

FIRING: Day 15. High-temperature firing occurs in two sequential kilns**, the first blown, coal-fired sinters the body, and the second with some coal, straw, and sometimes sawdust vitrifies the surface. High-firing of the pots in the blown-coal-fired, in-ground kiln #1 to a bright orange to orange-yellow heat occurs for about one hour, the last 10 minutes of which involve water-cooling of the outer wall and surrounding pit. This is followed by immediate transfer of the glowing-hot pots from the first kiln to the glaze kiln #2, *yòu yáo*, where they are set on a bed of straw, and sometimes sawdust and other field stubble. The hot pots provide the heat source. Once the lid is in place, a reduction fire erupts, and the pots remain in the kiln for about 35 minutes. This second firing takes only 15 minutes, and the outer chamber of the glaze kiln is water-cooled for about 20 minutes. The pots are removed to air-cool. The final step is testing the pots by tapping to determine if cracks are present, which happens to 1 in about 60 soup pots. The pots are then cleaned and set in storage sheds for sale, transfer to markets, or shipment overseas.

**These processes require input of the manager, his brother, or specialty trained skilled-laborer.*
***In reality, this function is often carried out by 3 kiln-firing specialists, strong men who are usually younger than the skilled potters and managers. They fire 5 loads of 50 to 60 of these soup pots in a day, about 275 soup pots total. Weather permitting, each workshop fires soup pots every 4 to 5 weeks.*

Because the Gaoxian workshop is small, in order to be more efficient, the potter organizes the work carefully. He says that can make 20 pots per day for five days in a row. Most objects receive no additional decoration (with only one potter, the workshop does not have the resources for extensive decorative work); but all require lids. The potter devotes one day solely to making all of the 100 lids for the pots made during the previous five days. One day per week, or night during the heat of summer, he and his wife focus solely on firing objects that have dried. During firing, vessels and lids that are awaiting the firing are placed for a short time on a shelf above the firing pit so that any remaining water in the pores will be driven off before the object is placed on the coals for firing.

Structural and Compositional Characteristics

The way that much traditional pottery has been made over a wide area in western Sichuan and eastern Tibet in the last 50 to 70 years seems to involve a three step process. An inverted bowl is shaped by pressing and paddling a round slab onto a convex or male mold that was placed on or attached to a kickwheel head. After partial drying, the bowl is detached from the mold and inverted. To elongate or narrow the form and to make the rim or mouth of the vessel, or to join several molded shapes, thick ring coils are joined and slowly paddled into an even wall thickness. Then rapid wheel rotation is used to throw and raise the wall. Not only are the vessels in Yingjing and Gaoxian made in this way, but this efficient and conservative forming technology seems to have been incorporated into pottery practice over a larger area. One of us has found large and small censers, bird medicine pots, and offering vessels that are made using this sequence in Gyantse, southwest of Lhasa. The censers are made by joining three differently sized, molded units. Glazed vessels 50 cm to 2 meters high for alcohol, pickled vegetables, grain storage, and solar hot water heaters found on roofs are made at a modern factory in Rongchang, west of Chongqing, that use the same forming sequence. In addition, a traditional pottery workshop in Rongchang (Fig. 3) uses this same sequence for soup and rice pots, hotpots, and braziers, and other evidence of this tradition is at the Rongchang Pottery and Kiln Museum, where examples from the now closed state factory were made using the same complicated sequence of manufacture that incorporates molding, coiling, paddling, and throwing.

Some of the evidence for this sequence of operations is found in Xeroradiographs of a Gaoxian hotpot (Fig. 13) and a Yingjing soup pot (Fig. 14). The texture of the Yingjing soup pot is much finer than that of the Gaoxian hotpot; however, both show evenly distributed and randomly oriented porosity in the molded sections, and horizontal and circumferential alignment of porosity at coil joints and diagonal porosity at the rims where throwing has occurred. The thrown lid, Fig. 13, upper left, lacks diagonally aligned porosity because it was thrown flat on the wheelhead with little force.

As shown in Table IIA, the compositions of raw materials and fired pottery contain some iron oxides, potassia, soda, magnesia, calcia, and some sulfate. The total flux content of the Mingshan clay is 8.53%, the Yingjing yellow clay is 11.66%, and the Gaoxian clay total flux content is 15.86%. The alumina to silica ratios are similar: the Mingshan yellowish-white clay, 32.93%, has the least alumina; the Yingjing yellow clay, 39.16%; and Gaoxian clay, 44.05%, the most alumina. Results for finished products are: Yingjing teapot, 37.75; the Gaoxian hotpot, 45.05%; and the Yingjing soup pot, 46.17%.

In addition to quartz and accessory minerals cited previously, the clays from Yingjing and Gaoxian are composed of 5-10μ platy particles, some of which have an approximate 120° angle between edges, typical of the two-layer clay minerals, illites or kaolinite, and these clays have a range of decomposition endotherms in the range from 790 to 900°C [9, 10]. However, the high potassium and iron oxides are typical of illites but not kaolinites; the calcium oxide is an impurity. The decomposition temperature of 790°C of the Yingjing clay is consistent with an illite and was acquired by differential thermal analysis from room temperature to 1100°C, heating 72 gms at 10°C/min. The yellowish white clay from Mingshan near Ya'an that is added to the clay body of teawares at Yingjing is an impure kaolinite with a higher decomposition temperature at 855°C and a slightly larger average particle size than the Yingjing and Gaoxian illitic clays (Fig. 15).

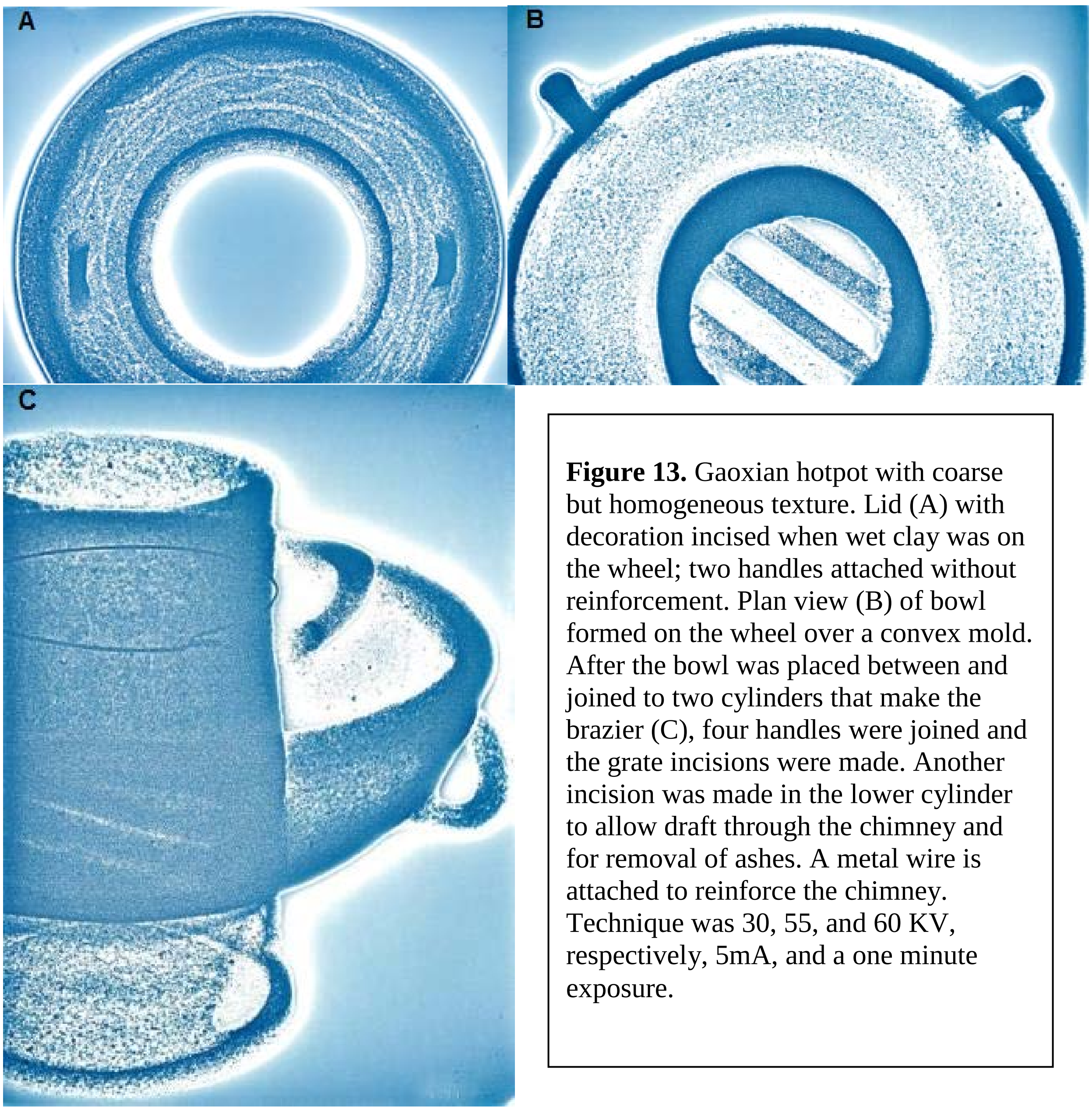

Figure 13. Gaoxian hotpot with coarse but homogeneous texture. Lid (A) with decoration incised when wet clay was on the wheel; two handles attached without reinforcement. Plan view (B) of bowl formed on the wheel over a convex mold. After the bowl was placed between and joined to two cylinders that make the brazier (C), four handles were joined and the grate incisions were made. Another incision was made in the lower cylinder to allow draft through the chimney and for removal of ashes. A metal wire is attached to reinforce the chimney. Technique was 30, 55, and 60 KV, respectively, 5mA, and a one minute exposure.

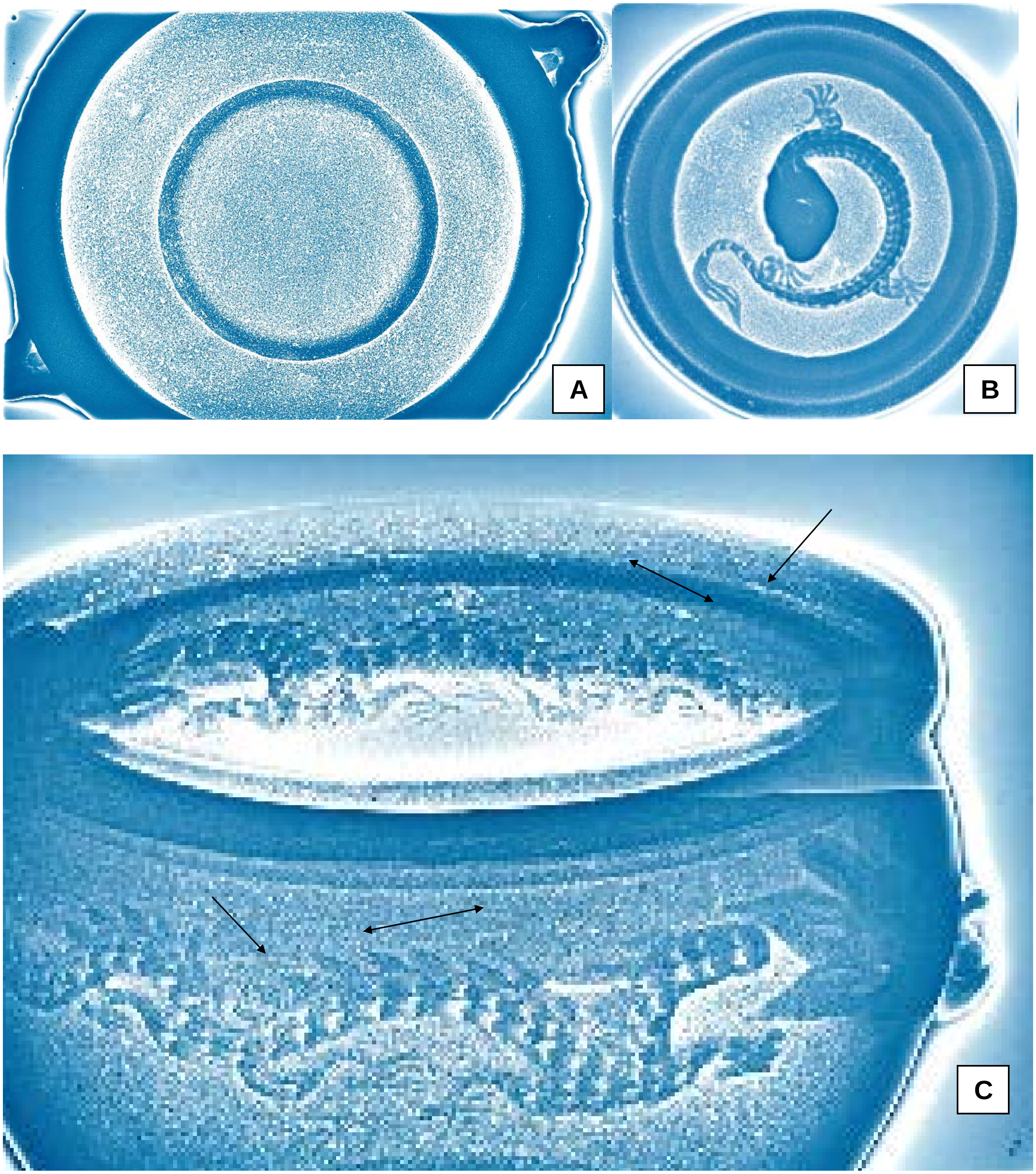

Figure 14. The Yingjing soup pot has a molded base and lower wall with randomly oriented porosity (A and C) and an upper wall with horizontal coil joints above the dragon and at the flange for the lid (single-pointed black arrows). These coils (C) were thrown on a fast wheel, shown by the diagonal alignment of porosity, as indicated by the double-ended black arrows set above the white-appearing lines of porosity. The lid (B) is decorated with a lucky dragon and has an even coarse texture with diagonal elongation of larger pores and strings of pores that indicates throwing. The two flanges of the lid are also visible.

Table IIA. Approximate Compositions of Raw Materials and Fired Ceramics, collected by EDS at 15 KV, 70-80 nA, for 3 minutes, over large areas at 50x.

Compound	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	MgO	Fe_2O_3	TiO_2	SO_3
Yingjing Clay	62.29	24.39	3.08	0.47	0.56	1.40	5.76	1.10	0.39
Gaoxian Clay	58.87	25.93	3.25	0.29	0.31	1.15	10.54	0.87	0.32
Mingshan Clay	67.91	22.36	2.66	0.62	0.00	0.85	3.09	1.23	1.11 Cl 0.2
Yingjing Soup Pot	57.89	26.73	2.01	0.54	0.70	0.79	9.06	1.23	0.59 0.47*
Yingjing Teapot	63.98	24.15	1.96	0.61	0.62	0.68	5.53	1.21	0.78 0.46*
Gaoxian Hotpot	58.00	26.13	2.07	0.61	0.76	0.74	9.32	1.19	0.77 0.40*

Table IIB. Approximate Compositions of Glazed Surface and Near-Surface Cross Section of Yingjing Soup Pot, collected by EDS at 15 KV, 70-80 nA, for 3 minutes, over large areas at 400-500x.

Compound	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	MgO	Fe_2O_3	TiO_2	SO_3
Surface	57.95	17.62	1.84	2.08	0.78	0.81	15.71	1.07	1.48
Glassy Near-Surface	50.40	17.75	1.57	1.39	0.73	0.77	23.94	2.02	0.88 Cl 0.3 *0.33
Polycrystal-line Near-Surface	47.56	41.78	1.23	0.79	0.62	0.44	5.27	1.09	0.65 Cl 0.1 *0.47

*Values for P_2O_5.

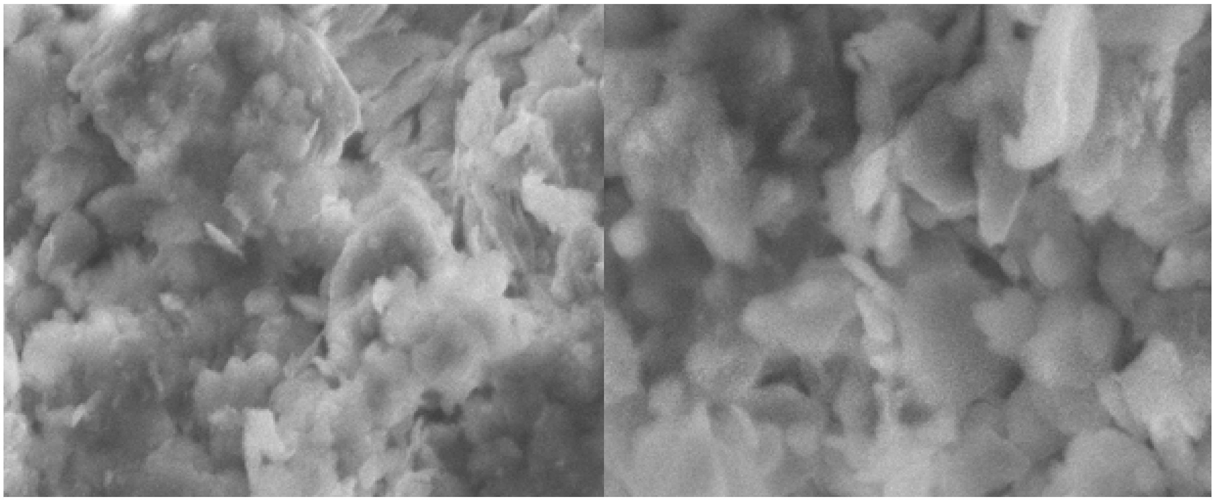

Figure 15. Microstructure of Yingjing yellow illitic clay at 5000x (left) (Gaoxian clay is similar), and Mingshan yellowish-white clay (right), possibly an impure kaolin, for teawares, also at 5000x showing some 120° angled edges and larger average particle size.

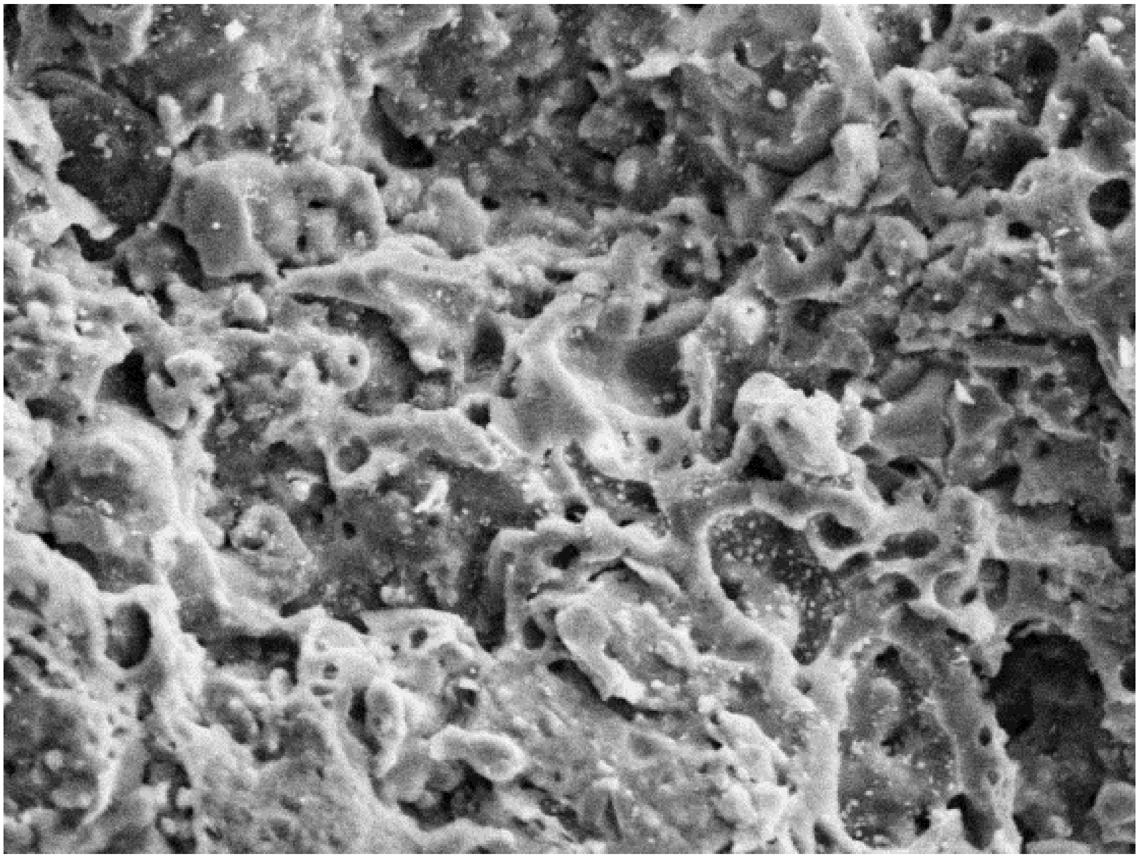

Figure 16. Vitreous structure of Yingjing soup pot with glass and many rounded pores, 3000x.

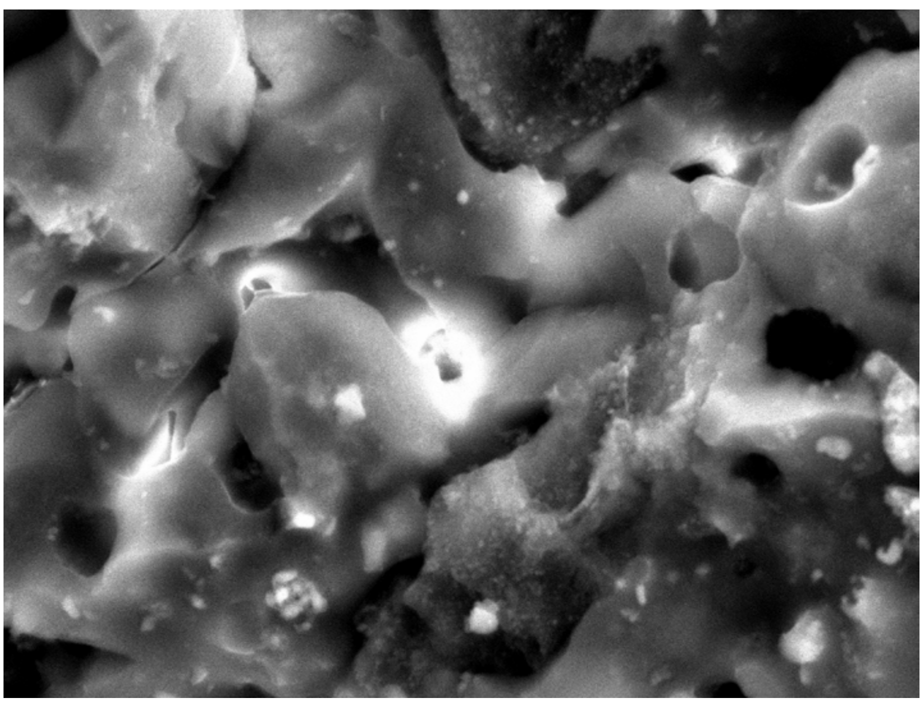

Figure 17. Enlargement of Fig. 16, showing well developed sintered microstructures of fired Yingjing soup pot at 8000x, with smooth surfaces on well-rounded pores and presence of fine rounded precipitates at glass-pore interfaces, perhaps mullite or an iron silicate.

The Yingjing soup pot displays a glassy, well-melted body with rounded pores that have smooth glassy walls, unlike the clay surfaces in Fig. 15. Most traditional and industrial practices would judge this microstructure to be overfired. In both Figs. 16 and 17, small precipitates are found in the fresh fractured glass that may be mullite or an iron silicate. Most of the surface of the Yingjing soup pot is covered with glaze (Fig. 18).

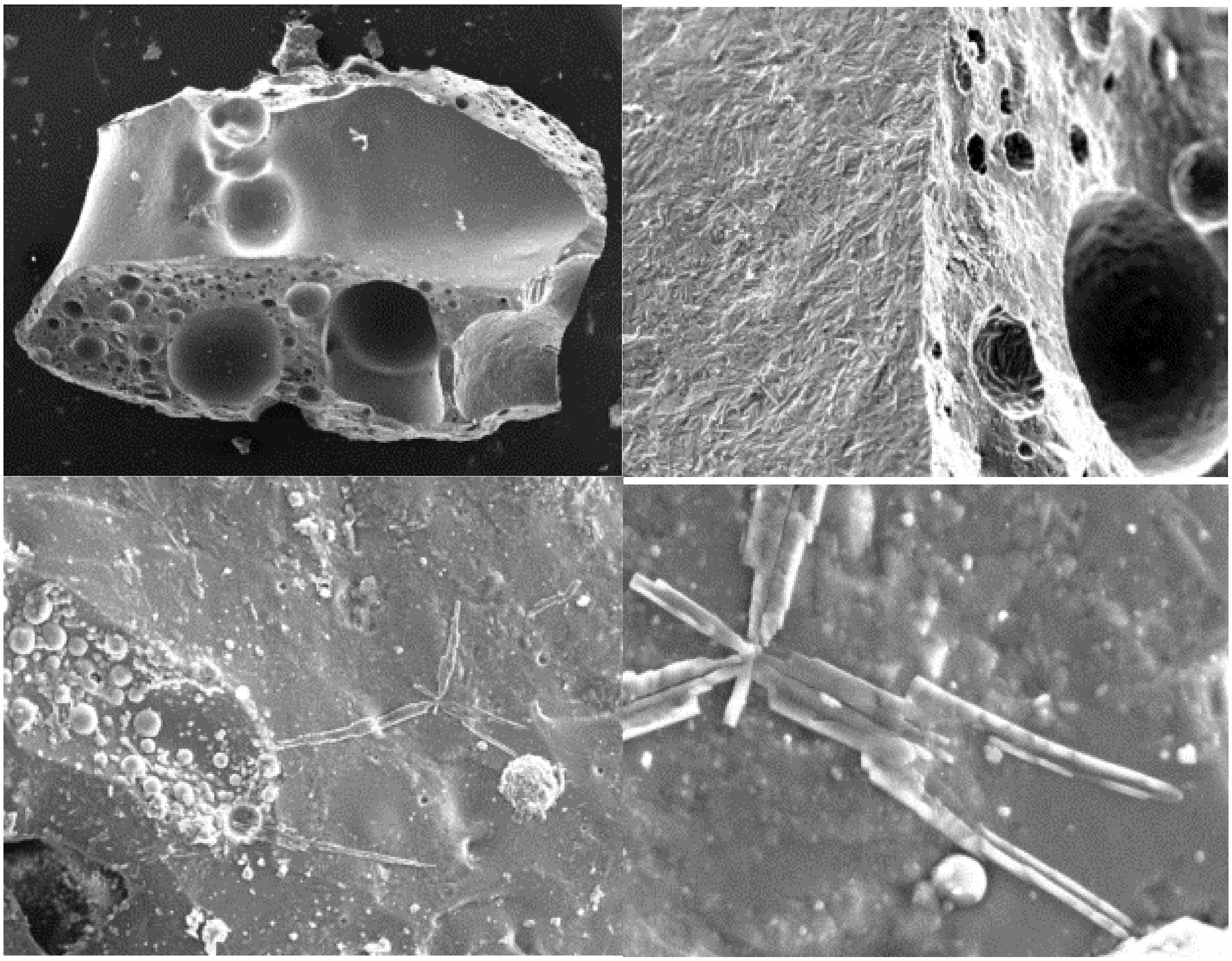

Figure 18. Upper left, cross section of glaze and glaze-body interaction zone, 50x; upper right, edge showing acicular crystals on the surface and bubbly reaction zone below; 500x; lower left, rounded and acicular crystals in the cross section of the glaze, 4000x; lower right, close-up of lower left with rounded crystals, and acicular branching crystals with right angle growth planes.

The Yingjing soup pot microstructure best matches a refiring temperature of 1150°C; 1200°C produces too glassy and well-sintered a microstructure; pores are too rounded and pore surfaces are too smooth. At 1100°C, there is no change in sintered microstructure compared to the original. However, some variation is to be expected; for instance, pots near the blower are fired higher, and sometimes bloat and warp. The 1150°C temperature agrees with the potter’s assessment of the firing temperature as being near 1200°C.

The Yingjing teapot (Fig. 19) was fired to the lowest temperature range. Fragments of the Yingjing lustrous glossy, black teapot handle were refired in an electric box furnace in oxidation (air) and reduction (nitrogen) from 700-1200°C, in 100°increments, with a ramp time of 5-10 minutes and a soak time of 15 minutes. At the end of each period of soaking, samples were removed from the furnace, allowed to cool, and a fractured cross section was studied at magnifications from 7-250x in a stereomicroscope and then, after mounting and using a vacuum evaporator to coat with carbon, the fresh fractured section was imaged at 5,000 to 10,000x in a SEM-EDS. At 800°C the surface gloss on the refired teapot fragments was somewhat lessened, and at 900°C it was altered visually in both oxidation and reduction firings. At 1100°C the firing temperature is clearly exceeded as the fracture surface is no longer matt but has considerable glass and polycrystalline facets. A firing temperature of 900 to 1000°C matches the internal structure of the refired teapot fragments and the steel-gray color. For teaware with a very glossy dark-black surface, as found on much of the heirloom ware in the village, a firing range of 800 to 900°is likely. Firing the unfired body to 700° results in a permeable product.

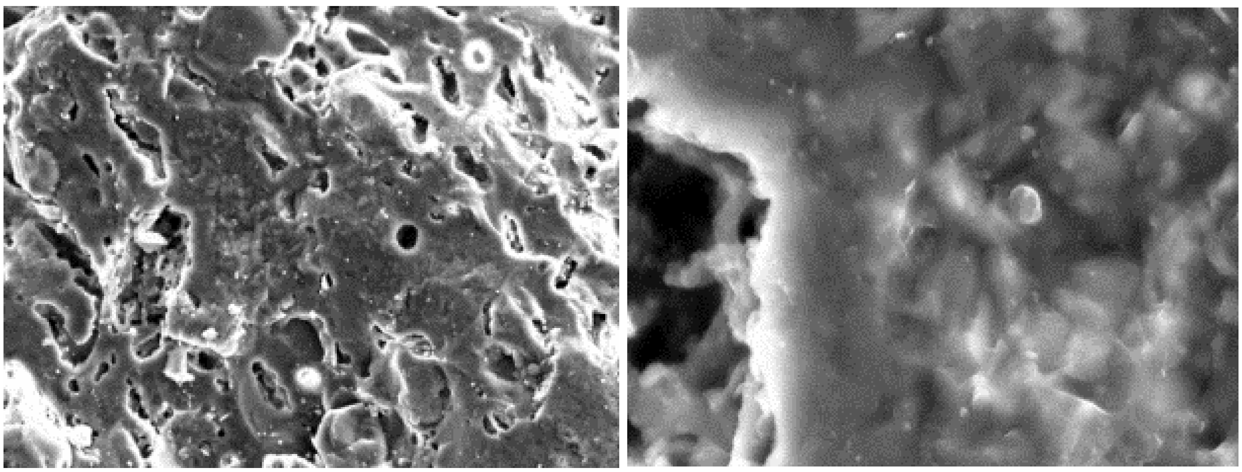

Figure 19. Fine vitreous structure of Yingjing teapot, fired to about 1000°C at 2500x (left) and center left area enlarged at 8000x (right). This very-fine particled microstructure appears much more like glass and mullite without the bloating seen in the Yingjing soup pot. The gloss on the pot starts to change from maximum lustrous surface at 700°C to less gloss at 800°C, and to low gloss at 900°C, and no gloss at 1000°C.

The Gaoxian clay is very heterogeneous and coarse, and the Gaoxian pottery has the lowest melting temperature because of high flux content and low alumina content. When firing in the DTA, a large exothermic carbon reaction appeared from about 250 to 750°C. The clay began to fuse into a glass at 1050° and by 1100° was bubbling and frothing in the crucible such that it commenced melting into a glassy but still heterogeneous material. At Gaoxian, a lesser control over raw materials selection and preparation is exercised, and the coal cinder addition acts to resist plastic flow, and so the firing is range is relatively low and the firing is fast.

The firing temperature of the Gaoxian hotpot is very difficult to assess because the body texture is heterogeneous and coarse, with much porosity and a glassy phase at the surface of coal-cinder particles that formed during their first firing. Thus, the microstructure is locally variable. By observation, we know that the firing temperature is lower than at Yingjing, 1050°C at Gaoxian and 1150°C at Yingjing. At Gaoxian we observed the first two firings of the day which are usually the least successful as the furnace is reaching equilibrium, takes a longer time to heat, and uneven heating occurs. Rather than being yellowish orange, the heat was orange. The fresh fracture of the Gaoxian hotpot fragment showed bimodal quartz, much porosity, and a well-sintered polycrystalline surface but without a lot of glass phase. At 1200°C, the fresh fracture is too vitreous, more than 50% glass; in fact, so much glass is present that the body might thermal shock when coals and wood were transferred to the inside grate for quick heating. At 1100°C, the fresh fracture is too glassy in oxidation and reduction, and we expect that the original firing temperature of the sherds was about 1050°C. One word of caution here is that the refiring took more time than the original firing, and so we may have pushed the reactions and sintering further here than in the original firing, so our temperatures may err on being on the low side.

Firing and Kilns

Yingjing. The kiln room at the Zeng workshop is located within a large open-sided but covered shed (Fig. 20). It houses the primary kiln pit with an electric blower, and removable lid; a smaller primary kiln with blower and lid, for making fine teawares; two glaze pits for use with the large primary kiln, and a single separate smaller teaware glaze kiln; storage spaces for coal to fuel the kilns and for sawdust and straw for use in the glaze pits; and areas to keep ring setters and finished wares just removed from the ash-glaze pit. A walkway crosses the middle of the shed; on the side opposite the firing area is a large space for drying and storing pottery that is awaiting firing or transfer to the exhibition gallery, or shipping and warehousing areas.

The base of the primary kiln (Fig. 21) is a shallow pit lined on the sides with refractory brick. A shallow layer of coal is shoveled onto the bottom of the pit for each session of firings. Pots are placed on top of the coals, but often isolated with supporting rings made in-house with the same coal cinder-clay mixture as is used for pottery. Draft is supplied by a small in-ground chamber next to the primary kiln that contains an air blower to force air into the coal to raise the temperature (Fig. 22). It was installed in the 1970s; before then, leather hand-pumped bellows required at least two people to operate throughout the firing. The removable hemispherical-domed lid of the kiln is made of a metal-mesh, reinforced ceramic. It is moved by lifting a wire cage with a chain and pole that is counter-weighted on the other end with a large rock (Fig. 23). This weighted pole is used to lift and swing the kiln dome on and off the kiln. A separate, smaller primary kiln and glaze kiln of similar design are located adjacent to the main kiln and are used for teaware and other smaller objects.

Objects are fired until they are orange hot, as seen through observation holes on the dome (Table III). After this oxidation firing, the surface layer of the pots is red while the interiors remain black. The dome is lifted and swung away from the firing pit, and the pots are quickly removed with long poles (or tongs for teaware) and placed immediately into one of two deep brick-lined pits in the ground in front of the kiln (Fig. 24).

The structures in front of the primary kiln are called glaze pits (*yòu kēng)* or glaze kilns (*yòu yáo*) (Fig. 24 and Fig. 25). A basket of resinous organic material (chips, straw, or sawdust from any resinous wood, or solids remaining after extraction of oil from rapeseed plants) lines the bed. The hot pots provide the only heat source. An iron lid is quickly placed over the top of the pit once all pots are inside, and the edges are sealed with dirt. As soon as the lid is in place, a reduction fire erupts (Fig. 26), and the burning organic material quickly combusts available air. After about 15 minutes the outer chamber of the glaze kiln is water-cooled for about 20 minutes, with water poured down the sides of the kiln into a surrounding porous chamber lined with ground brick fragments. Pots remain in the pit until nearly cool, and then are removed to finish air-cooling. After this reducing atmosphere, the surface skin becomes as black as the interior, and is covered by a thin, shiny silvery-grey ash glaze. The main purpose of this second kiln seems to be to allow the natural ash glaze to form on the surface of the pots; but interestingly, the workshop personnel insist that their pots are not glazed (since there is no deliberately applied glaze as is seen in many Chinese ceramics).

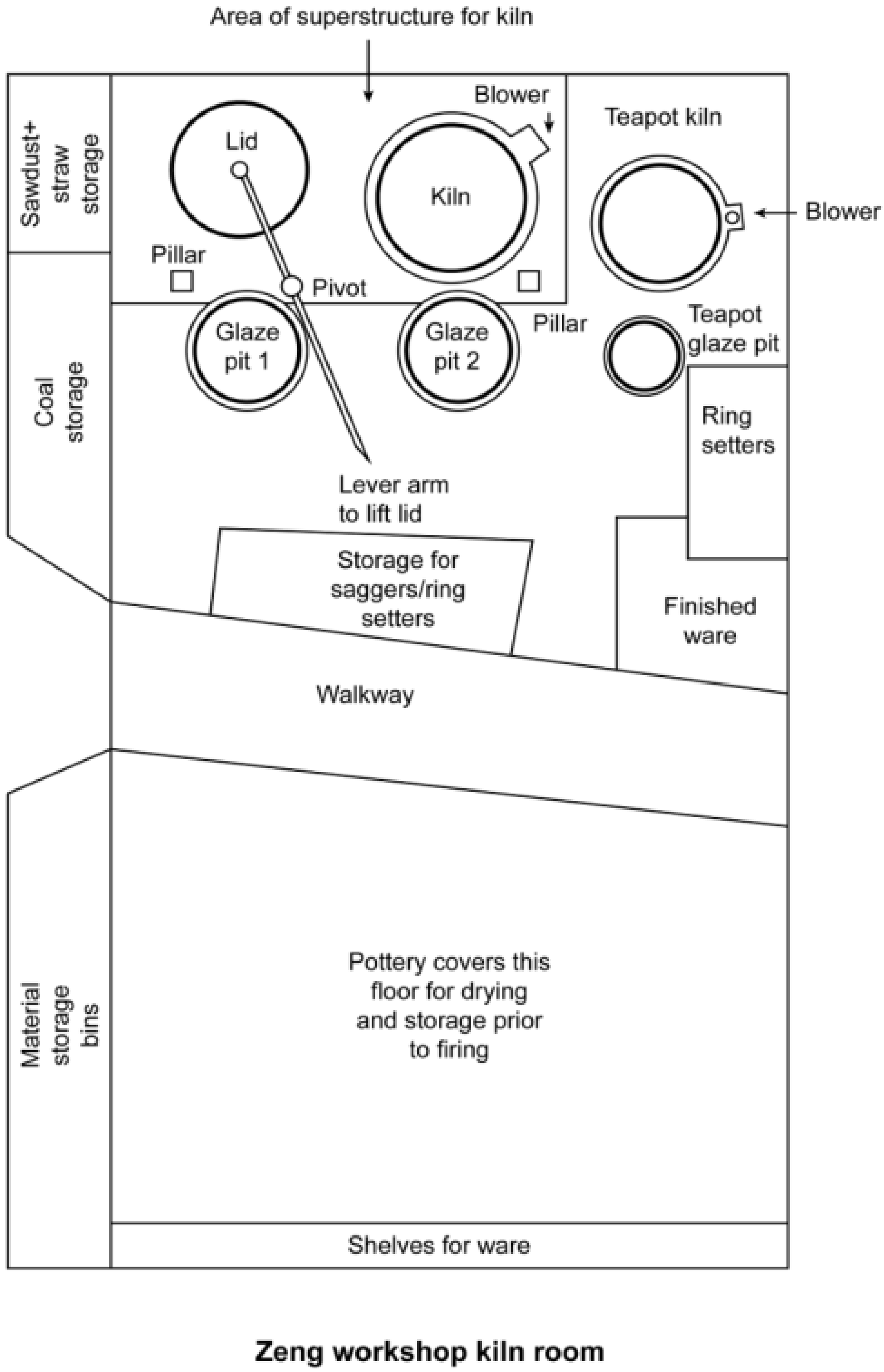

Figure 20. Layout of the firing shed in the Zeng workshop; rings are not to scale.

Figure 21. Primary firing kiln filled with coal cinders has dome cover behind; two glaze kilns at back left; in the foreground is the glaze kiln for teaware and the teaware kiln is off image at right.

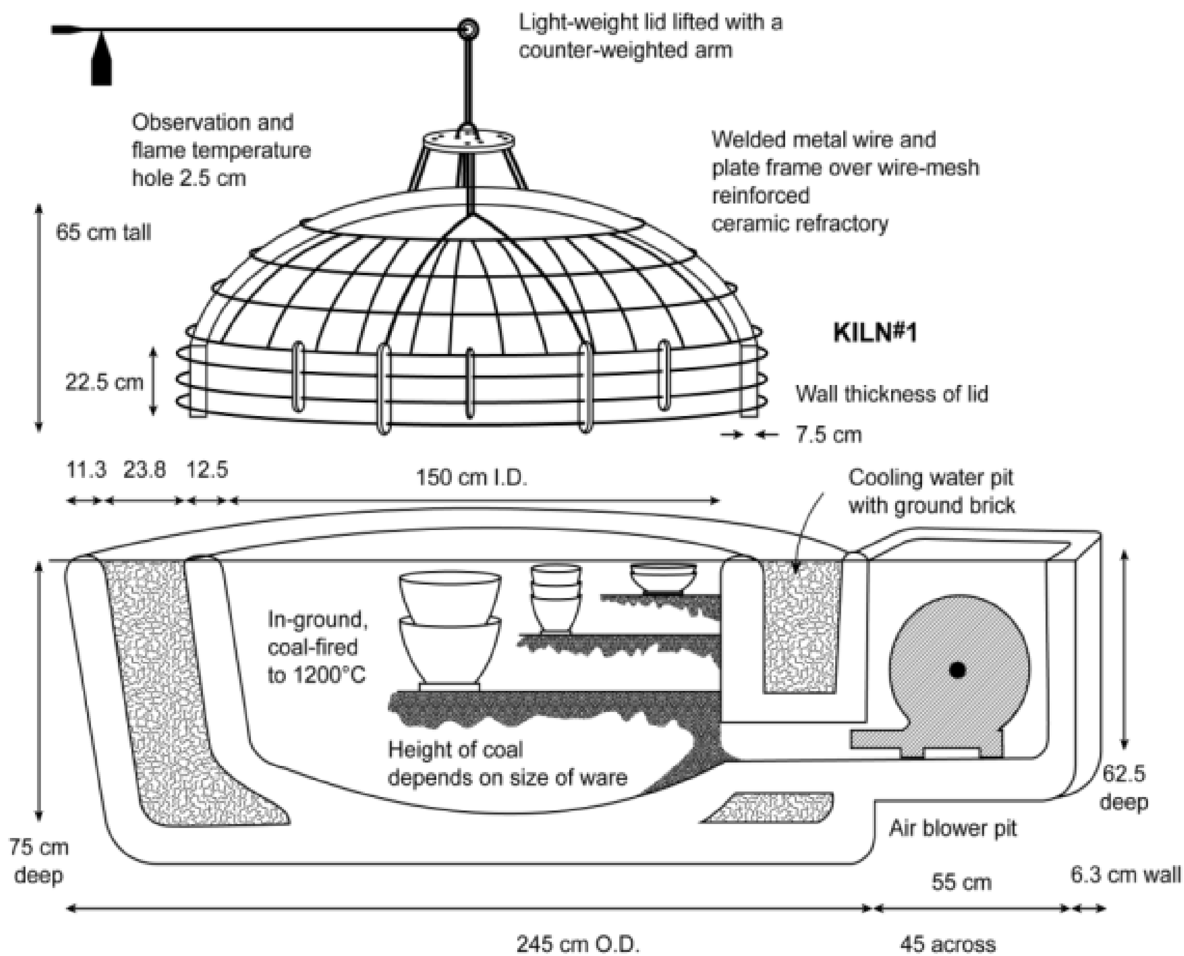

Figure 22. Cross section of the primary kiln at the Zeng workshop, Yingjing.

Figure 23. The kiln cover is levered off when pots are orange-hot. Note pots and lids above and behind the kiln, as well as setter rings, are preheating. These objects will be fired next.

Figure 24. Orange-hot pots are removed from kiln and immediately placed into a glaze kiln (shown in the foreground).

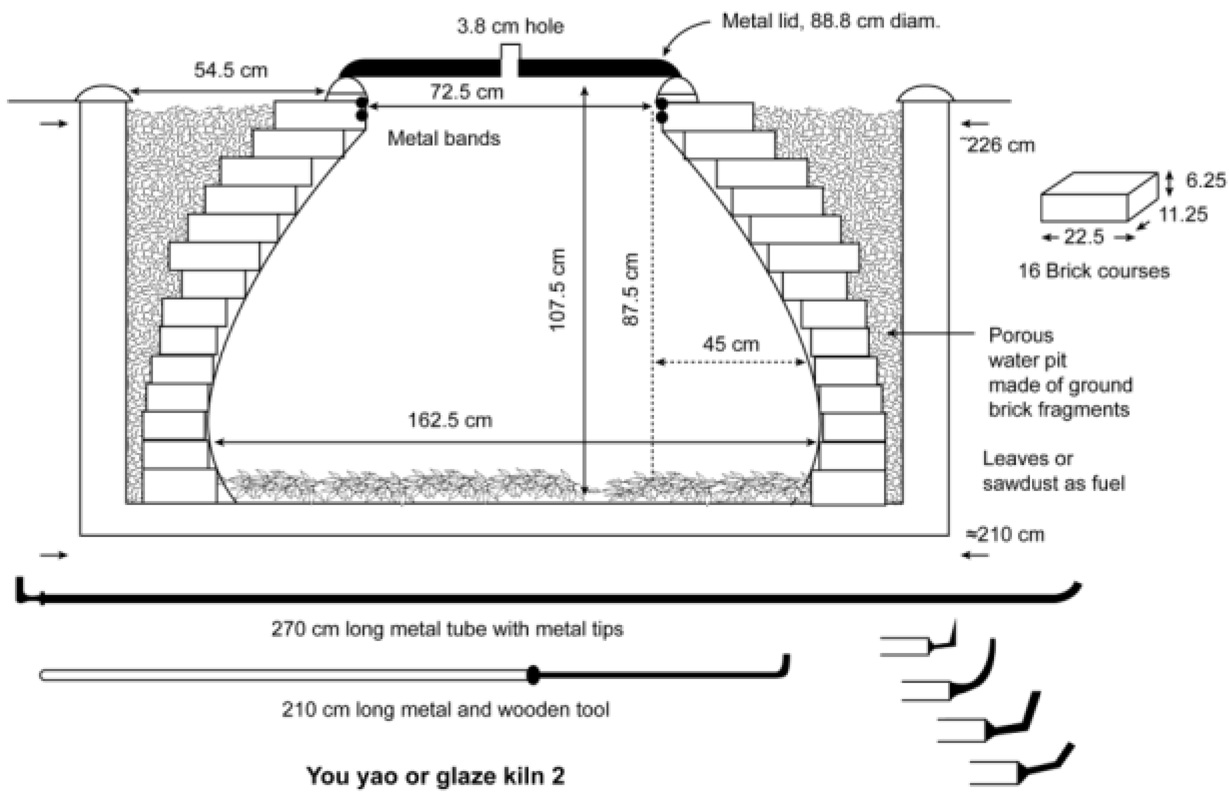

Figure 25. Cross section of the glaze kiln in the Zeng workshop, showing the brick structure of the kiln surrounded by the cooling-water pit.

Figure 26. A reduction fire releases flames and smoke when the metal lid is placed on the glaze kiln. The worker then immediately begins to prepare the primary kiln bed for the next firing.

Similar kiln and glaze kiln designs were seen at the other Yingjing workshops we visited. We observed that the workers running the firing process appear to rotate from one workshop to another. Hence, firing does not occur every day in any workshop we visited. After firing, when the pots are cool, any excess ashy material is scraped from the surface, especially along the rims of the pots and lids. Pots are checked and tested for cracks by tapping to hear a ring, with damaged objects that thud discarded. Lids are placed on pots, and they are transferred to a storeroom. As needed, they are taken into the gallery shop located in front of the workshop.

Table III shows the rhythm and timing of the paired two-kiln firing schedule as practiced in a workshop on a day when about 300 soup pots were fired.

Gaoxian. The same design of dome-covered kiln and glaze pit is used as in Yingjing, but both are much smaller (Fig. 27). The dome is set directly over the primary kiln dug into pre-heated coal, not over a brick-lined base. A single pot, placed directly on the hot coals, is fired for about 15 minutes, as a second primary kiln is pre-heated next to it. Then, the dome is lifted by lever and placed over a second pot in the adjacent primary kiln, and the first pot is moved while orange hot into one of the two glaze pits located in front of the primary kilns.

Figure 27. In Gaoxian, two pits are dug in a coal bed, one for pre-heating a single pot, the other for firing an already-heated pot under a small removable dome of similar design as in Yingjing.

These shallow glaze pits (Fig. 28) are pre-lined with the leaves of *Cinnamomum longepaniculatum* (油樟叶), a tree local to Gaoxian. After about five minutes, the pot is removed from the glaze pit to finish cooling on the ground nearby. They are then checked for cracks; the workshop experiences a 3-4% loss of pots due to damage incurred during firing. More detailed studies of the Gaoxian firing regimes is planned for future research.

Table III. Rhythm of the concurrent two-kiln firing schedule for soup pots in Yingjing. This firing was conducted with one primary and one glaze kiln. The schedule is for the third firing of the day and the beginning of the fourth firing, and includes firing in both the primary kiln #1 and in the glaze kiln #2.

High-Fire Kiln #1 sinters the body into a stable ceramic with low porosity and rocklike hardness; the duration of firing is about 53-67 min.		***High-Fire Glaze Kiln #2*** affects the surface texture and produces a somewhat glassy surface; the duration of firing is about 53 min, including heating and cooling and about half the loading and unloading.	
0-15 min.	Load and stack, usually 2 pots high		
3 min.	Turn on blower, and in 3 minutes, close the lid; coal bed glows but not the pots		
in 20 min.	Pots glow bright orange; flames exit around lid and small hole in lid; steep temperature ramp occurs to ~1150°C; 1 watches kiln, and 2 take short break		
20 min.	Soak at peak temperature		
10 min.	Turn off blower; add water to surrounding pit to begin to cool kiln, or at least to prevent further temperature increase		
7 min.	Transfer 60 glowing pots from kiln #1 to kiln #2	7 min.	Transfer glowing pots into kiln #2; place on a bed of straw/sawdust and/or sprinkle on top a coal/straw mixture if not hot enough
10 min.	Break	16 min.	Immediately replace lid and soak
15 min.	Load and stack 60 pots	30 min.	About 5 min. through stacking kiln #1, add water to pit surrounding kiln #2 and allow to cool
3 min.	Turn on blower, and in 3 minutes, close the lid; coal bed glows but not the pots		
18 min.	Kiln comes up to temperature while one watches and 2 on break	7 min.	Unload kiln to surrounding floor
22 min.	Soak at peak temperature	10 min.	Allow to air-cool
10 min.	Add water to outer surrounding pit and kiln temperature stabilizes and cools a bit	15 and more minutes	The kiln masters and other workers move pots away from the glaze kiln, separate the stacked pots; others clean and test pots by striking to hear ring, or, if cracked, dispose of them; then they stacked pots in nearby sheds while the pot transfer is taking place from kiln #1 to kiln #2
7 min.	Transfer glowing pots to kiln #2, as soon as completed pots are moved out of the way; take a break and start loading and stacking again		
The repeated cycle duration is about 85 minutes.		The repeated cycle duration is about 85 minutes, and a day's work for soup pots is 5 firings, or about 295-300 pots.	

Figure 28. In Gaoxian a **s**hallow ash-glaze pit with metal lid (no fuel, only leaves) is located in front of the primary pit (coal-fired to about 1050°C). The long, hooked rod for transferring pots is in the glaze kiln. A second pit and lid are in the background on the other side of the firing pit.

Properties of the Black Coal-Clay Ceramics

Yingjing. The majority of objects made in the Zeng and other workshops in Yingjing are the coarse-particle cooking and serving vessels, such as soup, stew and rice pots, or pots for steaming medicine. A smaller number of products are the fine-grained objects such as teapots and teacups. Thin-section petrography of soup pot sherds revealed a ceramic matrix with many pores in a variety of sizes and shapes. The Total Optical Porosity of scanned thin sections from typical cooking pots is 11-12% (Fig. 29). Open porosity measurements of coarse cooking wares show a high porosity of 15.29% ± 0.3% where n=3; while teapots, made with more finely ground raw materials, have an open porosity of 4.39% ± 0.15% where n=2. However, both types of products are unusually hard (Moh's hardness of the teapot is 7, and of the soup pot, 7-8). The glossiness of a gray teapot (3.3) was found to be only slightly higher than that of rough soup pots (2.05 ± 0.25, n=2).

These porosity values are high for stoneware, but the presence of such a large amount of pores of various size, shape, and number per unit volume can serve as sinks for cracks that propagate from mechanical and thermal shock and from strain due to variations in thermal expansion coefficients among the many phases present. The glaze layer with its rough surface and fine quartz particles is engineered to resist breakage. As well, the body with a 50 vol% clay and 50 vol% coal cinder is engineered to resist breakage. These ceramics are also unusually hard, between quartz and corundum. Fine-particled, low-expansion phases, such as mullite and anorthite, have nucleated and grown during the lengthy high-temperature burning of the coal. Such fine intergrown phases with a long thermal history resist fracture. Furthermore, the potters have limited the amount of glass that holds the coal cinders together but this glass also leads to plastic deformation of the pots at peak temperature. They fire quickly, within an hour to 1150°C, to further prevent the formation of large amounts of glass in the bodies that would provide crack paths through the body; thus, they have acted to make the best possible cook pots and braziers with the materials they have. A summary of this complex chemical cornucopia follows.

The great heterogeneity of the non-plastic particles of the clay and coal cinders creates internal variations in the melt that enhance the heterogeneity and variability of the ceramic bodies. Aplastic inclusions include those that likely entered with the clay, such as quartz, as well as others that are present in the coal cinder and ash (Fig. 30). Organic structures and glassy or fibrous silica particles are present in the coal cinder, as well as such minerals as partially melted feldspar remnants that are usually isotropic and covered with rods of mullite (Fig. 31). Quartz has sometimes melted and formed silica glass pools that seem to be concentrated in the vicinity of the melted and altered feldspars. In addition to remnant organics with replacement fibrous silica, anorthite and other phases are clearly derived from the coal cinders and have remained unaltered as the temperature achieved in firing does not exceed what the coal cinders attained during their original combustion.

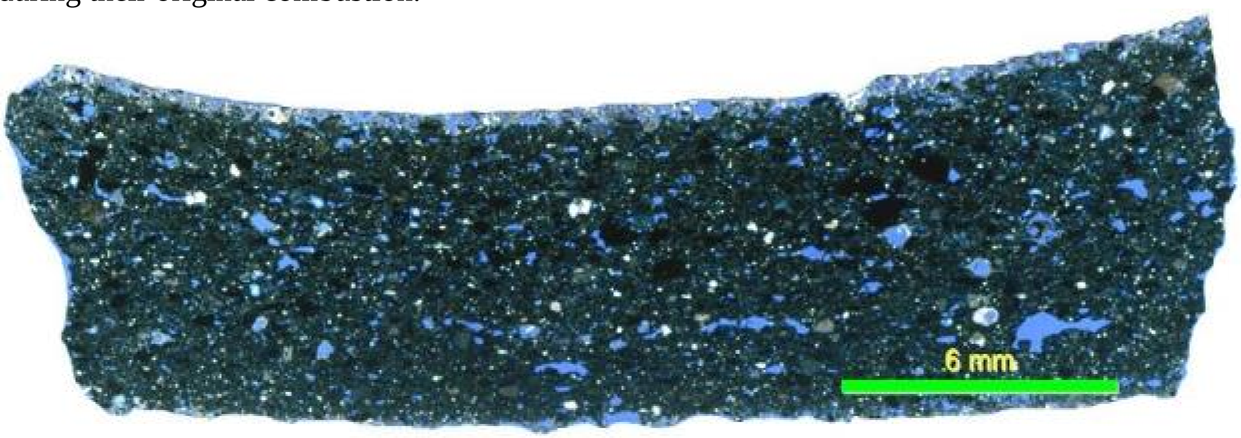

Figure 29. Yingjing fired soup pot thin section, scanned at 2.5 µm/pixel, shows 12% Total Optical Porosity (TOP) with pores in a variety of sizes and shapes. Extremely fine porosity is present in the ash-glaze layer on the upper surface of the sherd.

The thin ash-fluxed "glaze" surface is uneven and extremely porous (Fig. 32). It is glassy but filled with a combination of fine quartz grains, silica glass pools, black ash, and fine crystals that increase the opacity. A thin section stained with Na-cobaltinitrite and K-rhodizionate shows some enrichment of calcium in the glaze layer compared with the body that has stained pink, indicating that some of the very fine crystals are anorthite. The average thickness of this ash glaze found with several representative sherds is 200 µm, ranging from 0 at gaps in coverage to a maximum of 500 µm. Pores comprise one-third of the glaze area.

The many quartz particles in the ceramic body might promote thermal shocking because of the alpha to beta bending of the bonds at 573ºC. This inversion is associated with a change in size, which can lead to preliminary cracking during cooling of the body. These cracks would have a tendency to grow during use of the pot. However, the many near-surface rounded and glass-coated pores will likely absorb the cracks as they initiate, and it would require much energy to propagate them again. The coal chunks and ash, having many fine scale phases present, produce only small stored strain energy because they act over such short distances.

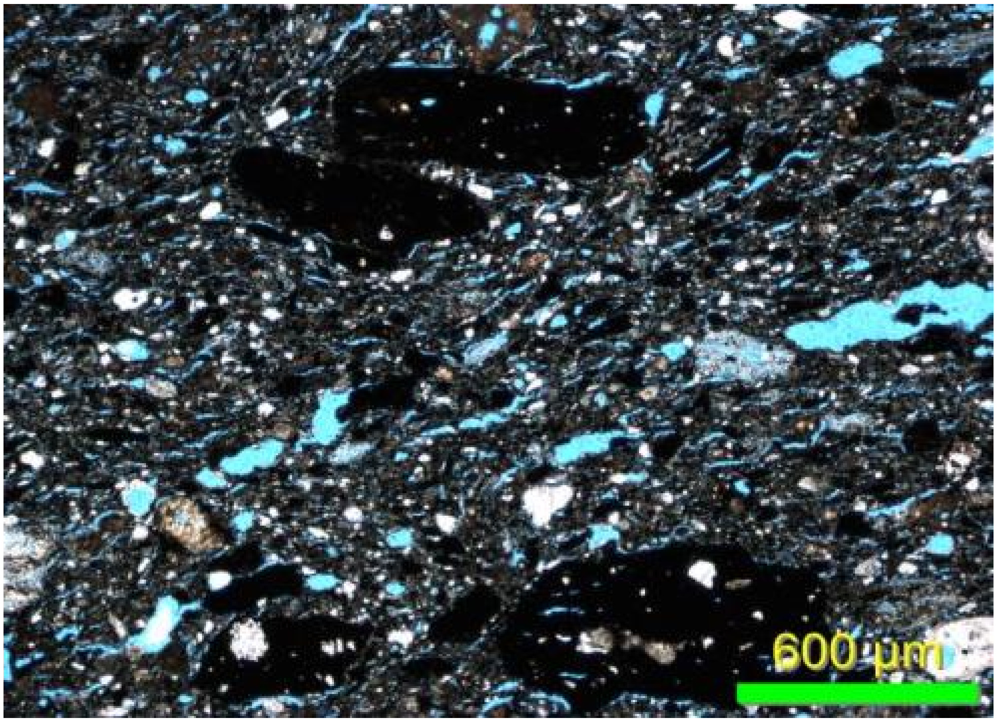

Figure 30. Yingjing soup pot thin section in plane polarized light is filled with fine-grained quartz, large fragments of coal, and smaller coal ash particles.

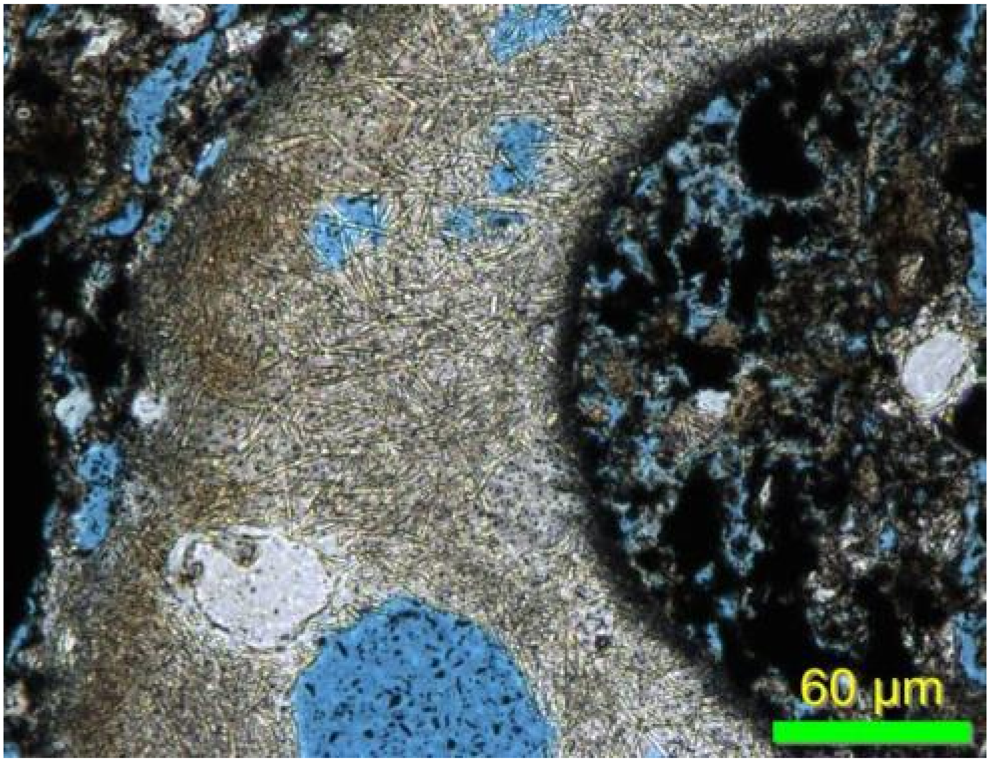

Figure 31. Many feldspar remnants contain mullite needles as shown in plane polarized light.

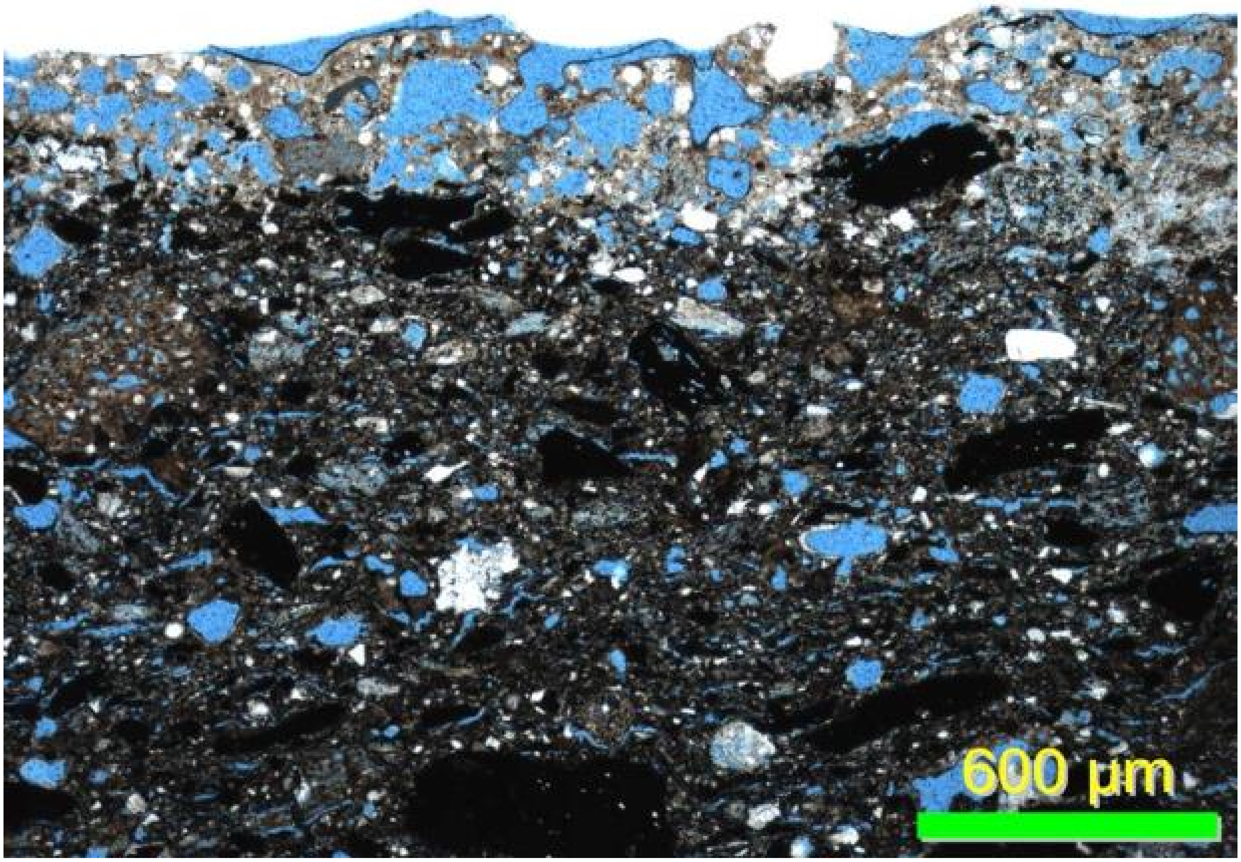

Figure 32. Yingjing ash glaze, extremely porous with glass filled with fine quartz particles.

Microscopy of a sample taken from a soup pot that was fired but which did not go into the glaze pit shows that the material is very similar to the fully fired and glazed sherds, except it is lacking the ash glaze layer. The Total Optical Porosity is essentially the same as for a fully fired sherd. While the sherd that did not undergo the glaze pit does have feldspars covered with fully developed mullite grains, there are fewer of them, especially in the interior. Instead, many of the interior feldspar grains have largely melted and so are isotropic, but are covered with tiny dots of just-nucleating mullite grains. The initial increase in temperature in the glaze pit when it is first closed off, and the organic material incinerating violently, may allow the growth of longer, well-developed needles of mullite on more of the interior feldspar remnants.
.

Gaoxian. The majority of objects made in this workshop are hotpots and braziers. The other products of this workshop are made of a similarly coarse material; the fine-grained teapots and teacups made in Yingjing do not appear in Gaoxian. Glossiness of these braziers is less than that of the Yingjing soup pots (1.0 versus 2.05 in Yingjing). In thin section this material shows similarities to the Yingjing material. It is very black, with coal chunks and powder, including distribution of much fine carbon. It is also very porous, with 11% Total Optical Porosity (so in the same range as the Yingjing sherds). The material is very inhomogeneous overall, with much fine-grained quartz, chert, and polycrystalline quartz likely deriving from both the clay and the coal cinders. Some of the quartz is cracked, indicating that the quick firing on very hot coals has caused some thermal shocking. There are also many discrete chunks of high-temperature phases originating from the coal cinders; these include very porous areas of silica glass, glass chunks filled with slender needles of mullite and anorthite, and iron oxide and carbon-rich glass chunks filled with large, thick anorthite rods.

Where secondary calcium carbonate filled parts of the organic structure within the raw coal, that infilling burned out during the original firing that produced cinders. There is now extensive anhydrite (calcium sulfate) present, some coming in from the coal cinders and some likely forming during firing from sulfur in the coal cinders reacting with calcium carbonate in the clay. This secondary anhydrite forms small equant grains with the rectangular pseudo-cubic cleavage typical of this mineral (Fig. 33). It is colorless, has moderate relief, very high birefringence, and some polysynthetic twinning; extinction is parallel to cleavage traces. It is unusual to see this mineral in traditional ceramic thin sections. There are also some very small patches, mostly on the edge of some anhydrite patches, of the hydrated form of calcium sulfate, gypsum. It has lower relief, a fibrous form, low birefringence, extinction parallel to cleavage traces, and polysynthetic twinning, and likely formed by post-firing alteration of the anhydrite.

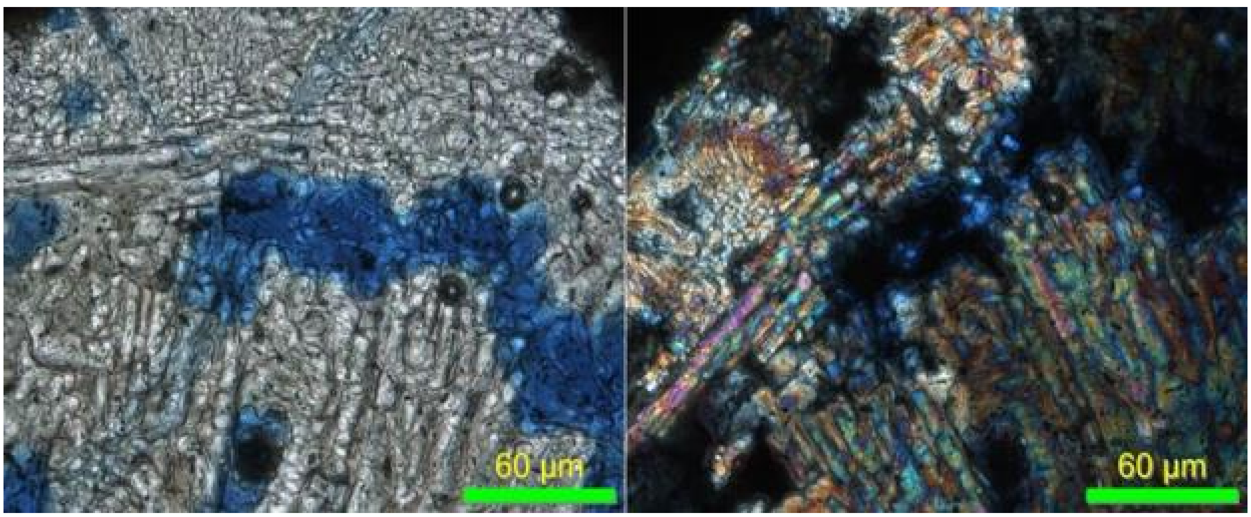

Figure 33. Gaoxian sherd in thin section with anhydrite formed as sulfur in coal reacted with calcium carbonate in the clay. Colorless in plane polarized light (left) with high birefringence in crossed polarized light (right), it has a distinctive rectangular pseudo-cubic cleavage.

The ash glaze on several representative Gaoxian sherds is much thinner than on the Yingjing ones (average 60 µm thickness, maximum 135 µm) so a little over one-fourth the thickness achieved in Yingjing). Coverage is also much spottier, with many long gaps in coverage on the surface where glaze thickness is 0 µm). This is likely due to the much shorter period of time the pots stay in the glaze pit in Gaoxian compared to Yingjing.

Design Development, Product Variation, and Markets

Yingjing. Medium to large cooking pots, such as soup or stew pots, make up the bulk of products (Fig. 34) in the Zeng workshop, but they also produce items such as braziers, teapots, and teacups (Fig. 35). About 60% of the products are sold locally, through their storefront located adjacent to the workshop. Buyers include residents of Yingjing and adjacent areas, as well as Chinese and foreign tourists who are drawn by advertisement of the "black sand" pottery of Yingjing as an Intangible Cultural Heritage of Sichuan Province. The remaining 40% is sold to buyers in more distant major cities around China; many repeat bulk buyers visit the storefront and choose pieces that they take back and sell in their own shops in other cities. The workshop also sells wholesale to website middlemen who then sell them online at their websites; they have 4-5 of these web retailers. Some of the other Yingjing workshops sell a larger portion of their products to specialized external markets, such as medicine pots to buyers in North Korea. Some workshops sell wholesale to web retailers, and a few have their own websites. However, the workshop owners are very conservative with production runs, and they test the market reception before investing time and capital in large production runs.

Design elements appear rather similar from one workshop to the next, but locals say that they can easily identify which workshop a pot came from because of slight differences in the manufacture, decoration, and shop signage. While there is overlap in types of products, each workshop also seems to have either some unique products, or different product lines that they emphasize. For example, some workshops at last visit were experimenting with glossier surfaces by applying a calcium carbonate wash prior to firing. This variation would help explain why so many workshops producing the same type of ceramics in the same town can all survive and find a customer base. However, decorative themes and styles evolve rapidly along the street and are copied with minor variations as shop owners see customers' preferences.

Figure 34. Large soup or stew pots are a popular Yingjing product, with surface embellishments and a silvery color and glassy surface texture.

We witnessed interactions at some of the shops and workshops between potters and customers, as when customers were observed entering the workshop to chat with potters and to view the firing process, or potters entered the attached shop to chat with and have tea with customers. This regular interaction with customers may be one factor in the explaining the presence of ongoing experimentation and innovation that can be seen in many of the workshops, as it would help potters to better guage consumer wants and needs. Strong interactions between workshops and their customers have been observed in other Chinese pottery towns as well [11].

Figure 35. Yingjing teapots, made with the finer-grained materials, are decorated with popular themes emblematic of Sichuan Province, such as bamboo (left) and pandas (right).

The value placed by consumers on unique pottery wares may also be enhanced when they can observe the production process, as often happens in Yingjing with its very dramatic firing procedure. Other researchers have found that being able to wander into a workshop to watch production serves to increase customer appreciation for, and valuation of, the resulting products [11, 12]. Customers admire the high level of skill and artisanry. Hence, these potter-customer interactions may also serve to create a stronger customer base and to enhance the loyalty of those customers, as well as to spur innovation among the potters, and perhaps to transform some of the pottery from strictly utilitarian to value-added, collectable art pottery.

Functionally Interesting Performance Characteristics

The most significant aspect of the Yingjing and Gaoxian pottery technology is the innovative use of a large amount, typically 50%, of powdered coal cinder mixed into the clay. This is not an additive choice that we have found in any other pottery technologies worldwide. This is an unusual way of making black pottery, a color much prized in many areas of China. The other highly significant aspect of the pottery technology is the unique two-step firing process. The kiln design, a shallow coal-fueled pit covered by a removable ceramic dome that is lifted up in the middle of firing so that orange-hot pots can be placed into an adjacent ash-glazing, bottle-shaped kiln, is also not something we have found with any other pottery technologies worldwide. Likewise, the rapidity of firing, reaching 1150°C in 20 minutes, is unparalleled. The creativity and innovation in this Sichuan pottery tradition is astounding.

The functional qualities imparted by porosity, by the amount, scale, and range of non-clay phases, the thin glassy surface glaze, and hardness--all favorably impact cooking, heat retention, and durability characteristics. The Yinging products are likely to be superior to the Gaoxian ones for some functions, and certainly for range of products, due to the raw materials available to Yingjing workshops, the more sophisticated milling and grinding processes, longer firing at higher temperatures, and longer glaze development regimes. The Yingjing workshops also have the advantage of more workshop personnel, and the creative interactions among personnel from all ten workshops that are active on the same street. However, we can confirm, from Gaoxian restaurant observation and cooking experiments (Figure 36) that even the Gaoxian products work quite well for cooking food and keeping it hot during a long meal.

Figure 36. A brazier, the most typical product of the Gaoxian workshop, has an interior silvery, bubbly, and glassy texture from the ash glazing process (left); in cooking use (right) with coals on the grate and ash collecting in the base. Different foods can be cooked quickly in succession to change and add to the flavor, and kept hot on the table during the course of a long banquet.

In Sichuan, pottery market forces associated with cooking and serving of food and beverages have a long history. Throughout China, it has long been important to host long meals where sharing food and drink are keys to social ties [13]; so the functional qualities of serving dishes are very important. A mid-Qing food scholar (ca. 1716-1797 CE) noted that the manner of serving dishes during a meal was crucial: a table should include vessels in a variety of shapes, and simmered food must be kept warm during the meal using only pottery, not metal vessels; serving with over-expensive porcelain was considered too ostentatious [14]. In Sichuan, pottery continues to be a material of choice for serving food and for keeping it hot during a meal, and sometimes for adding to the food to subtly change the flavor as new ingredients are added. Multiple serving vessel shapes all meet the same function of keeping simmered food warm for a long period, and traditional pottery continues to be valued for table use. Some of the reason for the continued use and enjoyment of this pottery may be found in a suggestion of David Pye [15]. Hand-made objects are interesting as much for their workmanship as for their design because the shapes, textures, and tactile qualities produced by artisans and craftspeople employ a craftsmanship of risk as they are working at the limit of their capabilities but with the assurance and efficiency of experience.

It was during the Qing period that significant changes occurred in Sichuan cuisine with importation of chili, tomatoes, maize, peanuts, and potatoes from the West in the 17th-18th centuries. Many new dishes appeared in response to these new crops. In Sichuan, maize and peanuts became especially important instigators of new dishes, and historical sources say that maize in particular “transformed agricultural life in Sichuan during the early Qing” [16]. During a period of great inventiveness in cuisine and the acceptance of many new foods, we expect an interest in new types of cooking and serving vessels. The now-ubiquitous Chinese practice of drinking steeped tea began in Sichuan Province, a place also famous from very early on for production of medicinal herbs [15]. Hence, it is not surprising to find special vessels for preparation of medicines and tea also embedded in Sichuan's pottery production.

Future research will include investigating additional data that may be available from archaeological efforts in Sichuan or Chongqing that may help shed light on the chronology and history of development and use of coal-clay pottery production. The connections between the Gaoxian workshop and Yingjing will also be researched, because it is highly likely that the Gaoxian technology and practices derived from Yingjing. Some possibilities are that potters from Yingjing migrated to the Gaoxian area, or that family connections led to some Gaoxian potters learning the technology in Yingjing. Another area of investigation is the past extent of coal-clay production in the Gaoxian area. It is possible there were at one time more workshops located here, or perhaps in the neighboring pottery-intensive town of Rongchang, or even in Chongqing; all of these possibilities will be further investigated.

CONCLUSIONS

The Sichuan coal-clay ceramic workshops have been highly innovative in the past. Potters experimented with and adopted a raw material mix not used by any other culture. They also carried out problem-solving to arrive at a unique and creative kiln design and rapid, two-stage firing process that is not seen elsewhere, but which meets their particular needs. The products they make with this innovative material and firing procedure are well suited to the cooking and serving functions that are so important in China, and especially for spicy Sichuan cuisine. They engineered a ceramic that resists fracture and thermal shock, even as coal and wood are being replaced with propane as the fuel of choice in restaurants. This pottery tradition is certainly worthy of its designation as an intangible cultural heritage. Many of the workshops continue to experiment on a regular basis, and so constantly produce new forms, designs, and product lines, while seeking new marketing strategies. This constant ability to innovate will likely help keep this tradition alive into the future.

ACKNOWLEDGMENTS

Funding for this research was provided by the National Science Foundation Program for Catalyzing New International Collaborations, the University of Delaware's Center for Global and Area Studies, and the Wenner-Gren Foundation for Anthropological Research. All fieldwork arrangements were made by our partner institution in Chengdu, the Sichuan Provincial Institute of Cultural Relics and Archaeology; we especially thank Gao Dalun, the Institute's Director. Paul Wallace of Imaging Cores is thanked for help with SEM-EDS. We also thank Zeng Qinghong in Yingjing, Huang Bin Xue in Gaoxian, and all of the other potters who graciously welcomed us into their workshops. Photo and drawing credits: C. L. Reedy, figures 1, 2, 4-6, 7 right, 8-10, 11 right, 12 right, 23, 24, 26-35, and 36 right; P. B. Vandiver, figures 3, 13-20, 22, and 25; and Y. Xu, figures 7 left, 11 left, 12 left, 21, and 36 left.

REFERENCES

1. C.L. Reedy, *Thin-section Petrography of Stone and Ceramic Cultural Materials,* Archetype, London, 2008.

2. C.L. Reedy, J. Anderson, T J. Reedy and Y. Liu, Image Analysis in Quantitative Particle Studies of Archaeological Ceramic Thin Sections. *Advances in Archaeological Practice* 2(4), 2004, pp. 252-268.
3. C.L. Reedy, J. Anderson and T.J. Reedy, Quantitative Porosity Studies of Archaeological Ceramics by Image Analysis. In: P.B. Vandiver, W. Li, C. Maines and P. Sciau, eds., *Materials Issues in Art and Archaeology X*, Cambridge University Press, Cambridge, 2015, doi# 10.1557/opl.2014.711.
4. W.D. Kingery and P.B. Vandiver, *Ceramic Masterpieces: Art, Structure, Technology,* Free Press, New York, 1986.
5. P.B. Vandiver, Variability of Song Dynasty Green Glaze Technology Using Microstructure, Microcomposition and Thermal History to Compare Yaozhou, Jun, Ru, Yue, Longquan, Guan, and Korean Koryo Dynasty Materials and Practices. In: N. Shi and J. Miao, eds., *Proceedings of International Symposium on Science and Technology of Five Great Wares of the Song Dynasty,* Science Press, Beijing, 2016, pp. 391-432.
6. Frederick Matson, personal communication to P.B. Vandiver, Fall 1984.
7. P.B. Vandiver, W.A. Ellingson, T.K. Robinson, J.J. Lobick and F.H. Seguin, New Applications of X-radiographic Imaging Technologies for Archaeological Ceramics. *Archaeomaterials* 5(2), 1991, pp. 185-207.
8. P.B. Vandiver and C.L. Reedy, Traditional Craftsmanship and Technology of Jianyang Black Wares from Fujian, China. *Studies in Conservation,* 59 (S1), 2014, pp. 169-172.
9. R.C. MacKenzie, *Differential Thermal Analysis*, Academic Press, London, 1970, pp. 317-321.
10. W.W. Wendlandt, *Thermal Analysis,* John Wiley, New York, 1986, pp. 373-380.
11. G. Gowlland, Style, Skill and Modernity in the *Zisha* Pottery of China. *Journal of Modern Craft,* 2(2), 2009, pp. 129-142.
12. R. Dilley, The Visibility and Invisibility of Production among Sengalese Craftsmen. *Journal of the Royal Anthropological Institute,* 10(4), 2004, pp. 797-813.
13. A. P. Underhill, *Craft Production and Social Change in Northern China: Fundamental Issues in Archaeology,* Kluwer/Academic/Plenum, New York, 2002.
14. J. Spence, Chi'ing. In: K.C. Chang, ed., *Food in Chinese Culture: Anthropological and Historical Perspectives,* Yale University Press, New Haven, 1977, pp. 259-294.
15. D. Pye, *On the Nature and Art of Workmanship,* Cambridge University Press, London, 1968, pp. 3-40.
16. K. C. Chang, *Food in Chinese Culture: Anthropological and Historical Perspectives,* Yale University Press, New Haven, 1977.